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Subsurface Environmental Assessment for Four Geothermal Systems

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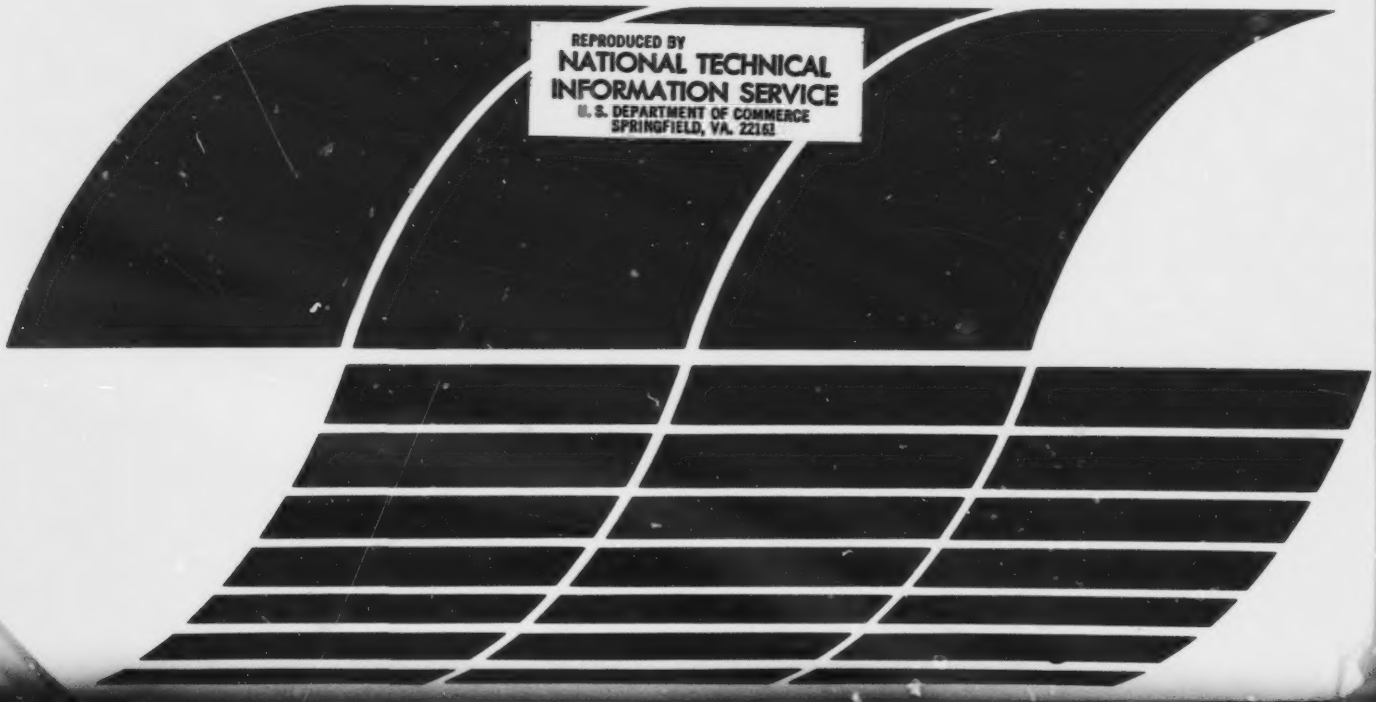

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16. ABSTRACT

This is the second in a series of reports concerning the environmental assessments of effluent extraction, energy conversion, and waste disposal in geothermal systems. This study involves the subsurface environmental impact of the Imperial Valley and The Geysers, California; Klamath Falls, Oregon; and the Rio Grande Rift Zone, New Mexico.

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GEOTHERMAL ENVIRONMENTAL IMPACT ASSESSMENT
Subsurface Environmental Assessment for Four Geothermal Systems

by

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LAS VEGAS, NEVADA 89114

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FOREWORD

Protection of the environment requires effective regulatory actions which are based on sound technical and scientific information. This information must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of specific pollutants in the environment requires a total systems approach which transcends the media of air, water and land. The Environmental Monitoring and Support Laboratory-Las Vegas contributes to the formation and enhancement of a sound monitoring data base for exposure assessment through programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment

- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs

This report is the second in a series of five reports covering the following subjects:

- baseline geotechnical data for four geothermal areas in the United States

- subsurface environmental assessment of geothermal development

- a guide for decision makers

- a pollution control technology guidance manual

- a groundwater monitoring methodology for geothermal developments

The first two reports cover the baseline data necessary for the development of the fifth report which will contain the strategy for monitoring change in groundwater quality as a result of any geothermal resource development, conversion and waste disposal.

The third report will be a guideline for those persons charged with responsibility for issuing permits for geothermal exploration, development, conversion and waste disposal.

The fourth report will cover justification of the need, by way of regulatory or anticipated regulatory requirements, for control of constituents of raw wastes and a description of waste control technology alternatives.

For further information on these reports, contact the Monitoring Systems Research and Development Division of the Environmental Monitoring and Support Laboratory, Las Vegas, Nevada.

George B Morgan

George B. Morgan
Director
Environmental Monitoring and Support Laboratory
Las Vegas

ABSTRACT

Geothermal systems are described for Imperial Valley and The Geysers, California; Klamath Falls, Oregon; and the Rio Grande Rift Zone, New Mexico; including information on location, area, depth, temperature, fluid phase and composition, resource base and status of development. The subsurface environmental assessment evaluates potential groundwater degradation, seismicity and subsidence. A general discussion on geothermal systems, pollution potential, chemical characteristics of geothermal fluids and environmental effects of geothermal water pollutants is presented as background material.

For the Imperial Valley, all publicly available water quality and location data for geothermal and nongeothermal wells in and near the East Mesa, Salton Sea, Heber, Brawley, Dunes and Glamis KGRAs have been compiled and plotted. The geothermal fluids which will be reinjected range in salinity from a few thousand to more than a quarter million ppm. Although Imperial Valley is a major agricultural center, groundwater use in and near most of these KGRAs is minimal. Extensive seismicity and subsidence monitoring networks have been established in this area of high natural seismicity and subsidence.

The vapor-dominated Geysers geothermal field is the largest electricity producer in the world. Groundwater in this mountainous region flows with poor hydraulic continuity in fractured rock. Ground and surface water quality is generally good, but high boron concentrations in hot springs and geothermal effluents is of significant concern; however, spent condensate is reinjected. High microearthquake activity is noted around the geothermal reservoir and potential subsidence effects are considered minimal.

In Klamath Falls, geothermal fluids up to 113°C (235°F) are used for space heating, mostly through downhole heat exchangers with only minor, relatively benign, geothermal fluid being produced at the surface. Seismicity is low and is not expected to increase. Subsidence is not recognized.

Of all geothermal occurrences in the Rio Grande Rift, the Valles Caldera is currently of primary interest. Injection of geothermal effluent from hydrothermal production wells should remove any hydrologic hazard due to some potentially noxious constituents. Waters circulating in the LASL Hot Dry Rock experiment are potable. Seismic effects are expected to be minimal. Subsidence effects could develop.

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Project Management: Geonomics, Inc., H. Tsvi Meidav, Project Manager, and Subir K. Sanyal, Deputy Project Manager.

General Section and Imperial Valley: Geonomics, Inc., Richard B. Weiss, Subir K. Sanyal and Theodora Oldknow.

The Geysers and Klamath Falls Sections: GeothermEx.

Rio Grande Rift Zone Section: W.K. Summer and Associates.

Editor: Geonomics, Inc., Evelyn Bless.

Donald B. Gilmore, the Project Officer, was responsible for administration and general guidance of the project for the U.S. Environmental Protection Agency.

SECTION ONE

GENERAL CONSIDERATIONS

1.1 INTRODUCTION

This is the second in a series of reports concerning the environmental assessment of effluent extraction, energy conversion and waste disposal in geothermal systems. The primary objective of the study is to provide the U.S. Environmental Protection Agency (EPA) with a monitoring approach to detect any ground water pollution caused by geothermal resource development. This approach is expected to serve as a model for monitoring any geothermal area. An important part of this study involves subsurface environmental impact assessment of geothermal development in four areas: Imperial Valley and The Geysers, California; Klamath Falls, Oregon; and the Rio Grande Rift Zone, New Mexico (Fig. 1.1). Each of these areas is representative of a distinct type of geothermal system. The Imperial Valley is representative of an intermediate to high temperature, liquid-dominated system; The Geysers, of a vapor-dominated system; Klamath Falls, of a low temperature, liquid-dominated system; and Rio Grande Rift, of a hot dry rock system, and a high temperature, liquid-dominated system.

The first report in this series prepared by Geonomics, Inc., is titled "Baseline Geotechnical Data for Four Geothermal Areas in the United States" (in press). That report includes compilation and assessment of baseline data on geologic, hydrologic, climatic and seismic conditions, as they pertain to potential subsurface environmental impact, in each of the four geothermal areas mentioned above. The present report defines, within the limits of available data, the geothermal systems and potential subsurface environmental impact of geothermal energy development in each of the four areas. From the data base provided by these assessments, a monitoring system will be designed, implemented and evaluated at one of the four areas.

1.1.1 Objectives

The objectives of the overall study are to acquire and analyze data for the purposes of:

a. identifying pollutants as a result of geothermal development,

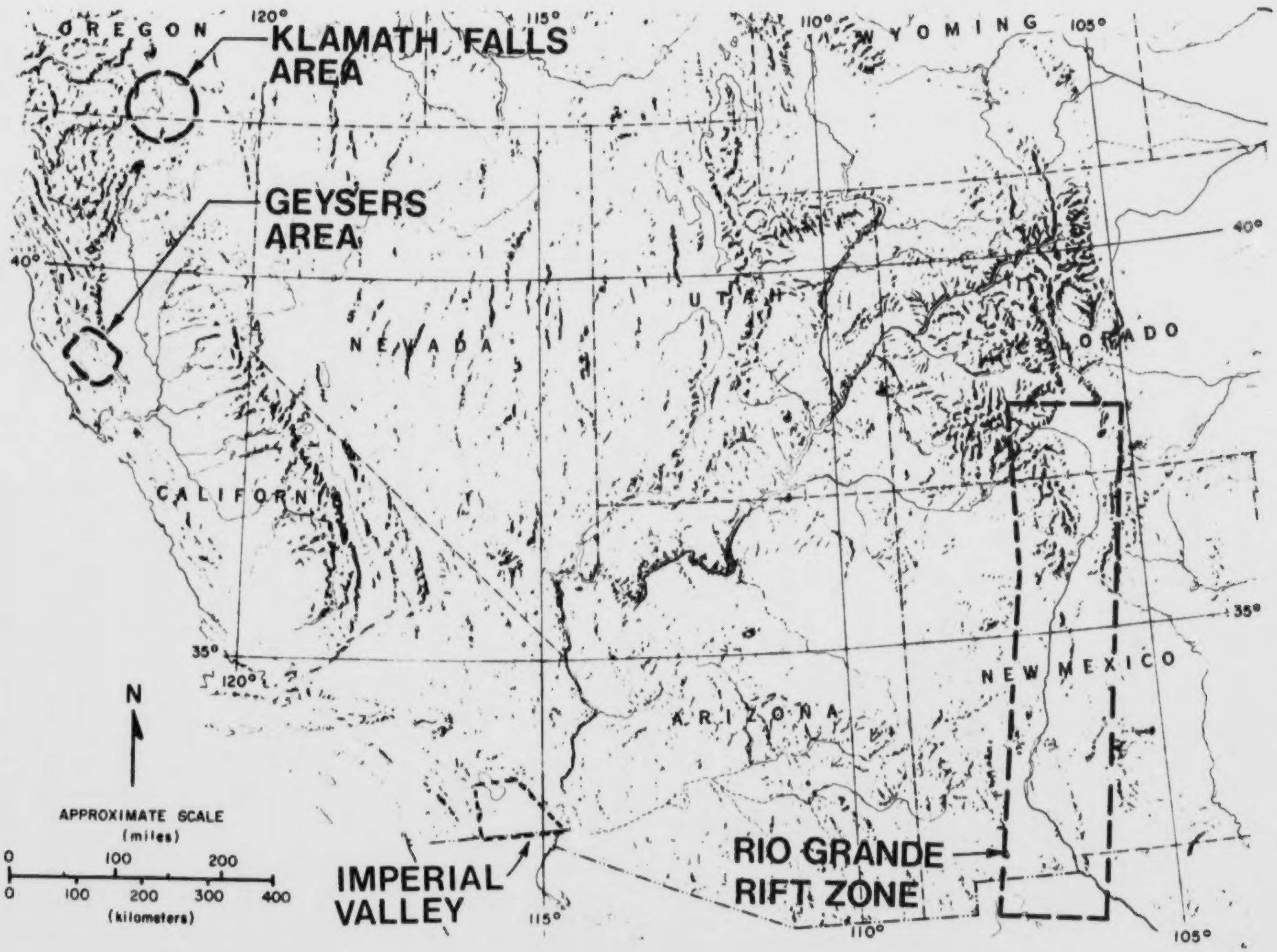

OREGON
KLAMATH FALLS AREA
GEYSERS AREA
WYOMING
NEVADA
UTAH
COLORADO
CALIFORNIA
ARIZONA
NEW MEXICO
IMPERIAL VALLEY
RIO GRANDE RIFT ZONE
120°
115°
110°
105°
40°
35°
N
APPROXIMATE SCALE
(miles)
0
100
200
0
100
200
300
400
(kilometers)

Figure 1.1 Location of study areas

b. identifying pathways into the underground water environment,

c. identifying ecological hazards involved with long-term operating facilities,

d. designing a groundwater monitoring approach that will be applicable to any geothermal resource development and conversion facility, and

e. applying the methodology to a selected site and operating the system to verify its applicability.

The primary emphasis is on the environmental effects of changes in the groundwater regime, both chemical and hydraulic, as a result of geothermal resource utilization. The environmental effects to be considered are potential groundwater pollution, subsidence and induced seismic events, which in turn may affect the ecology and socioeconomic conditions of the area.

1.1.2 Scope of Investigation

The scope of work is outlined in five tasks to be accomplished in three stages. Stage I is an assessment stage that includes Tasks 1 and 2. Task 1 defines the geology, hydrology, climatology and seismicity of the four geothermal areas, including identification of aquifers. Task 2 defines the various geothermal systems and quantifies the pollutants from geothermal resources development, including phase of the produced fluids, subsidence possibilities, seismic effects, fluid disposal methods and thermal losses, and their possible effects on the groundwater of each area. This report is the result of the Task 2 investigation.

Stage II is a design and research stage that includes Task 3, resulting in the design of a groundwater monitoring system for one of the four areas.

Stage III includes Tasks 4 and 5 and is a groundwater monitoring, analysis and evaluation stage. Task 4 involves implementation and operation of the monitoring program under the direction of the Project Officer. Recommendations for improvement in the monitoring plan will be incorporated into Task 5. As a result of the experience in designing and operating a monitoring system, recommendations for a general groundwater monitoring methodology that will be most apt to meet the requirements of any geothermal resource development will be the culmination of Task 5.

1.1.3 Subsurface Environmental Impact Report

The first (Task 1) report (Geonomics, in press) of this study considered baseline geotechnical data on the four geothermal areas. This second (Task 2) report defines the geothermal systems in each area. To the extent that data are available, the definition of the system includes location, area, depth, temperature, phase of fluid, chemical composition of fluids, estimated resource base and recoverable heat reserve, the status of field development, projected development, existing well data and anticipated operational problems. Another aspect of Task 2 is the identification and quantification of potential pollutants in the geothermal effluents from each of the four areas. The third aspect of Task 2 is to assess, within the limits of available data, the potential subsurface environmental impact of geothermal resource development in each of the four areas. The so-called "subsurface" environmental impact study considers timely underground environmental factors such as groundwater quality and seismicity, but also some near-surface but aboveground environmental factors such as chemical and thermal pollution of surface water bodies and subsidence of the ground surface. This study specifically excludes consideration of aboveground environmental factors such as air and noise pollution. The remaining facet of Task 2 is consideration of the available and anticipated technologies of disposal of the geothermal pollutants.

Based on the Task 1 and Task 2 reports, a monitoring program can be formulated for each of the four geothermal areas, and more important, a general monitoring strategy can eventually be developed that will be applicable to any geothermal area.

1.2 BACKGROUND

Geothermal resources are a relatively new source of energy. The first electrical power generator, utilizing geothermal steam, was operated at Larderello, Italy, in 1904. The first geothermal power plant was established at the same site in 1913. New Zealand began harnessing geothermal energy for electricity in the 1950s. The next major development was at The Geysers in the United States in the 1960s. Suddenly, in the 1970s, geothermal energy development became an important goal in national planning in many countries. This turn of events was precipitated by the "energy crisis" of the early 1970s. By 1976, the total geothermal electrical power capacity in the world had reached 1,325 MW, the new geothermal electrical power producers being Mexico, Japan, El Salvador and the U.S.S.R. In the United States, the present generating capacity of geothermal electrical power is 502 MW. The goal of the U.S. Energy Research and Development Administration (ERDA) is to achieve a minimum geothermal electrical power capacity of 6,000 MW by 1985 and more than 20,000 MW by the year 2000 in the United States.

While electrical power production from geothermal resources is a relatively new industry, geothermal steam and hot water have been used in various forms in many countries from time immemorial. For example, the use of geothermal water for balneological purposes has been popular in many parts of the world since biblical times. More recent nonelectrical uses of geothermal energy include space heating, process heating, greenhouse operation, etc. A number of countries, for example Hungary and Iceland, have developed considerable capacity for nonelectrical uses of geothermal energy. In the United States, space heating by geothermal energy has been in use for several decades in Klamath Falls, Oregon, and Boise, Idaho. The growing shortage of natural gas is expected to cause a rapid increase in the utilization of low-grade geothermal heat for direct heat uses, the high-grade geothermal resources being lucrative sources for electric power production.

It is interesting to note that although geothermal water has been used for therapeutic purposes for millennia and as an energy source for decades, not until the 1970s has any serious concern been expressed about its possible adverse environmental impacts. Traditional belief in the therapeutic value of natural hot water may have delayed concern about environmental implications of geothermal development. The expansion in geothermal capacities and volume of hot water use has coincided, however, with the new environmental consciousness of the past decade.

Environmental impact data relevant to geothermal resource development are sparse, since there are only three sites in the world (Lardarello, Italy; Wairakei, New Zealand; The Geysers, U.S.A.) with a significant history of geothermal power generation. The existing data on the nature of pollutants in geothermal fluids are inadequate, considering their extreme diversity in chemical composition (see section 1.3.3). However, effort has begun in earnest during the last few years to collect data on geothermal fluid pollutants and their effects on the environment. Considerable research is also being carried out to improve technology and to develop new methods to control pollution due to geothermal fluids. Research and development programs are being sponsored by government agencies such as EPA and ERDA, resource companies, utilities, etc. The environmental awareness of the late 1960s and 1970s has given birth to important legislation, at both federal and state levels, to safeguard the environment. Most of these regulations do not specifically address geothermal pollutants; they nevertheless have a strong impact on the geothermal industry as discussed in the following section.

1.2.1 Legislative and Regulatory Aspects

The following federal laws and regulations, applying to all industrial development, are also relevant to the geothermal industry:

1. National Environmental Policy Act (1969)
2. Clean Air Act as amended (1970)
3. Federal Water Pollution Control Act Amendments (1972)
4. Noise Control Act (1972)
5. Marine Protection, Research and Sanctuaries Act (1972)
6. Wilderness Act
7. Fish and Wildlife Coordination Act
8. Endangered Species Act (1973)
9. Safe Drinking Water Act (1974)
10. Resource Conservation and Recovery Act (1976)
11. Toxic Substances Control Act (1976)

Most of these laws provide for and encourage relegation of enforcement power to the state, and sometimes to the local government level, upon satisfaction of certain requirements. Three other federal laws concerned wholly or in part with geothermal energy development have some bearing on the environmental impact aspects. These laws are:

1. Geothermal Steam Act (1970)
2. Federal Nonnuclear Energy Research and Development Act (1974)
3. Geothermal Energy Research and Development Act (1974)

A discussion of the provisons of these laws and those listed earlier is beyond the scope of this report. Besides these federal laws, the state and local governments have their own laws and regulations. Most of these regulations are closely related to and implement federal regulations. These state and local regulations may impose more restrictions but cannot reduce the restrictions placed on pollutant discharges and emissions by federal rules. It should be noted that as yet there are no federal discharge and emission standards for geothermal pollutants. As a result, some of the states are developing stringent and perhaps arbitrarily restrictive regulations on acceptable pollutant levels in discharges or emissions from geothermal operations. Diverse requirements by various political jurisdictions may unduly increase the cost and reduce the pace of development of geothermal energy. EPA, in cooperation with the

Interagency Geothermal Coordinating Committee (formerly Geothermal Advisory Council), is developing an interim, "recommended" set of standards for geothermal pollutants (EPA, 1977b). This set of standards is not to be construed as enforceable, but as a guideline based on available information and formulated in coordination with state environmental agencies and appropriate private organizations. Eventually, as the geothermal industry becomes well established, equitable and legally enforceable standards for geothermal effluents are expected to evolve.

1.3 GEOTHERMAL SYSTEMS

1.3.1 Geothermal Resource Types

Five broad classes of geothermal resources are usually recognized: hot water, dry steam, "geopressured" hot water, hot dry rock, and magma. The following discussion of these classes is largely extracted from Sanyal (1976) and Chen, et al. (1976).

Of these types of geothermal resources, the first three exist as "reservoirs," implying a body of stored fluid in the pore space of a subsurface rock formation. Geopressured hot water reservoirs are those that contain hot water at an abnormally high pressure. The hot dry rock geothermal resource is a heat resource which may have to be exploited by flowing a fluid through fractures created artificially in otherwise impermeable rock. Electrical power generation from dry steam reservoirs has been practiced profitably for many years at The Geysers in California and at Lardarello, Italy. The technology of power generation from hot water reservoirs has been amply demonstrated at various places in the world, for example, New Zealand, Mexico, Japan, U.S.S.R., etc. The other types of geothermal resources have not been proven commercially feasible at the current state of technology. Hence the rest of this report will focus on dry steam and hot water reservoirs only.

Essentially, a geothermal reservoir is a hot, porous rock formation containing fluids. Such reservoirs are encountered typically where the earth's crust is thinner than usual, at the boundaries of tectonic plates, and in areas of geologically recent volcanism. These conditions give rise to higher than normal geothermal gradients, making it possible to extract commercially useful hot water from a relatively shallow depth. Under unusual circumstances, even an area of normal geothermal gradient can provide water hot enough for some uses, such as space heating. The definition of an economically extractable geothermal resource is intimately dependent on both physical and economic factors: the quantity and physio-chemical properties of the water in the reservoir, the distribution, quantity and depth of wells necessary for production, the type of production and utilization facilities, operating procedures and practices, and costs of alternative energy sources in the area. An economic geothermal resource at one place may be considered noncommercial at some other location.

In areas of thin crust, tectonic plate boundaries or geologically recent volcanism, molten rock may occur at a relatively shallow depth. Heat is transferred to the overlying solid rock mass by conduction. Percolating surface water becomes heated by heat transfer from the rock. This creates large scale natural thermal convection cells through the porous rock. In many geothermal reservoirs a cap rock layer of very low vertical permeability prevents the escape to the surface of ascending hot water. In some cases the hot water reaches the surface either because of lack of a cap rock or by seepage along faults, giving rise to hot springs, geysers, fumaroles, etc.

Hot Water Reservoirs--

These reservoirs are so defined because liquid water is the continuous, pressure-controlling fluid phase. White and Williams (1975) define a "hot water system" as having a water temperature greater than 150°C (302°F). One can infer continuity of the liquid phase from reservoir pressure distribution and the abundance of certain chemical constituents that are soluble in water but have low vapor pressures, and hence lack significant solubility in low pressure steam. The most critical constituent in distinguishing hot water systems from dry steam systems is the chloride ion. Most metal chlorides have high solubility in water and the chlorides are easily leached from most rocks by hot water. These metal chlorides by and large have negligible volatility at temperatures as high as 400°C (752°F), and do not have appreciable solubility in low pressure steam.

The vast majority of known geothermal systems are hot water reservoirs at elevated pressure, and produce steam due to flashing as the fluid pressure drops in the well bore or at the surface. The steam quality (i.e. the percentage of steam in the total effluent) of the well effluent is a function of many variables: the flow rate, bottom-hole temperature and bottom-hole pressure of the fluid; presence of chokes and valves; and the wellhead pressure. However, the initial fluid temperature and the final separating pressure are by far the most critical parameters that determine steam quality at the steam separator. For example, water flashed to a separator pressure of 3.51 kg/sq cm (50 psig) from an initial temperature of 300°C (572°F) yields 33% steam; 200°C (392°F) yields 11% steam; 150°C (302°F) yields less than 1% steam. The temperature of hot water reservoirs ranges from near ambient to 370°C (698°F).

Hot water reservoirs generally display higher contents of arsenic, boron, chloride, cesium, fluoride, lithium, sodium, rubidium, and silica than cooler ground water. Plugging of the porespace around well completion and scaling in the well bore, pipes and surface equipment often occur in hot water systems. Silica precipitation is the most important cause of these problems because quartz is the most abundant natural mineral and its solubility increases rapidly with temperature. Less commonly, calcite, zeolite, sulfides and clay minerals may also cause plugging problems. Geothermal waters with very high or low pH will be highly corrosive in some cases.

Dry Steam Reservoirs--
These reservoirs produce dry (superheated) steam with no associated liquid. Such systems are relatively rare. So far only five major dry steam reservoirs have been definitely identified worldwide. These reservoirs are located at The Geysers, California; Larderello, Italy; Matsukawa, Japan; Omikobe, Japan; and Monte Amiata, Italy. These reservoirs are characterized by temperatures in the range of 220° to 250°C (428° to 482°F) and pressures around 35 kg/sq cm (500 psia). Wells in dry steam reservoirs normally produce superheated steam with a few degrees of superheat. Condensate from the steam usually has very low total dissolved solids (TDS) content. The steam usually shows low concentrations of chloride (less than 15 parts per million [ppm]) and high concentrations of boron, ammonia, sulfate and magnesium. The steam may contain a considerable amount of noncondensible gases such as hydrogen sulfide and carbon dioxide. At The Geysers these concentrations may be greater than 5 ppm for boron, and average 194 ppm for ammonia, 222 ppm for hydrogen sulfide and 3,260 ppm for carbon dioxide (Reed and Campbell, 1976) (see section 3 on The Geysers).

1.3.2 Pollution from Geothermal Operation

Exploration and Development Phases--
During the exploration, development and construction phases of a geothermal conversion system, the sources of environmental pollution are likely to be transient and of minimal consequence in the long run. Such pollution may include construction material and vegetation debris; noise, machine exhaust and dust; disturbed soil; waterborne silt, mud solids, drill cuttings, cement, etc.; and accidental spills or well blowouts. Blowouts are usually preventable by proper drilling practices. All of the types of pollution listed above are minimized by enforcement of state and federal regulations on noise, solid waste and other pollutants.

Production and Utilization Phase--
The main source of pollution during the operation of a geothermal energy conversion facility is the geothermal fluid itself; noise and possible change of landscape are minor factors. Depending on the nature of the geothermal fluid and the design of the conversion facility, the environmental impact may range from negligible to very serious. The pollutants in the

fluid are: dissolved and suspended solids, dissolved and entrained gases, products of chemical reactions between the fluid and the materials it comes in contact with, and waste heat.

Theoretically, environmental pollution is prevented if the conversion facility is a closed system. In such a system, all the fluid is reinjected into the reservoir after power conversion (or heat-exchange, in case of direct heat use) in a closed loop from the production to the injection well. Such closed loops can be designed for both binary and flash power conversion systems. However, high cost or technical problems may make a perfectly closed loop impractical. At the other extreme, a completely open conversion facility can be designed so that all waste liquid and gases after power conversion (or heat-exchange) are released untreated to surface drainage or the atmosphere. Such a system potentially would present the worst possible case of geothermal pollution. However, the extent of actual pollution would depend on the chemical characteristics of the geothermal fluid. In some geothermal reservoirs, the water is potable, and consequently, discharge of untreated waste geothermal water into surface water bodies might be acceptable. If a geothermal fluid must be treated for constituent removal (for example, in order to avoid scaling of pipes) prior to injection, a considerable amount of solid waste may be created. The solids may, at one extreme, have commercial value as useful chemicals. At the other extreme such solid wastes may be harmful chemicals subject to confinement and other regulatory control.

In reality, a geothermal conversion system will be somewhere between the extremes of the totally closed and the totally open systems. The exact extent of pollution of the atmosphere, land, and surface water bodies will depend on the amount and nature of pollutants in the waste and the rate, volume and disposal methods. The amount and nature of pollutants in the waste will depend on the chemical characteristics of the geothermal fluid as well as the conversion process. It must be pointed out that even in a completely closed system, there will be some thermal pollution.

Even if the conversion system design eliminates any discharge of waste into the aboveground environment, the possibility exists of potential chemical and thermal pollution of ground water aquifers during injection of waste. Several possible situations where reinjection of waste geothermal fluid may cause pollution of ground water include the following potential pollutant pathways or mechanisms:

1. Well seal or casing deterioration or failure
2. Escape of reinjected fluid through structural or stratigraphic pathways

3. Hydrofracturing or confining formations with high pressure injection

4. Accidental spills

5. Percolation from evaporation ponds (enhanced by higher temperatures)

6. Percolation from discharge of mineralized fluids through surface conveyances

7. Chemical migration due to osmotic forces

Well seal deterioration or failure would allow fluids to flow vertically up or down the well bore, depending on where the failure occurred. Well casing deterioration or failure would allow escape of fluid directly into the stratigraphic unit adjacent to the failure. This could occur by corrosion or shearing of the casing. At The Geysers, wells drilled on landslides have had blowouts when the landslides reactivated and the downslope movement sheared the well casing. Vertical movement of fluid up and/or down the wellbore could occur, again the extent would depend on where the failure occurred and the effectiveness of the initial cement seals.

Structural and stratigraphic pathways, such as faults, ineffective caprock or buried stream channels may allow fluid to travel along pathways that have not been previously recognized. Hydrofracturing of confining formations due to high pressure injection may also create structural pathways in the form of micro-fractures or joints.

Accidental spills at the surface, percolation from evaporation ponds, or percolation or leakage from surface conveyances would entail similar pathways. The fluids would percolate from the surface downward directly into the nearer surface aquifers. A spill, if not contained, would also discharge fluid directly to surface streams, lakes or canals.

Osmotic forces can cause slow migration of chemical constituents of the waste fluid to a groundwater aquifer through an intervening caprock, which may act as an osmotic membrane. However, pollution due to this effect is anticipated to be extremely minor and insignificant.

1.3.3 Chemical Characteristics of Geothermal Fluids

The chemical characteristics of geothermal fluids vary over a wide range, in both the number of chemical species and their concentrations. For example, TDS range from about 50 to 388,000 ppm and pH from 2 to 10 units. From the environmental impact point of view, the geothermal waters can vary in character from entirely benign and potable to highly corrosive and saline. The fluid characteristics may vary from one reservoir to another, from one well to another in the same reservoir, and with time in the same well.

The geographical variation in the chemical characteristics may be attributed mainly to variation in the nature of the subsurface rocks, temperature, and distance from the source of recharge, if any. The temporal variation in the chemistry of geothermal fluids at a particular site can have a number of causes, the most important being the variation in the rate of fluid recharge (natural or by injection) into the reservoir. Table 1.1 lists reported ranges of gross chemical properties of geothermal water. The table also indicates the reasons for measuring these properties. Table 1.2 is an exhaustive compilation of the concentration ranges of various chemical constituents in geothermal waters. The data are largely taken from Tsai, et al. (in press). The right hand column in Table 1.2 lists pertinent comments on each of the chemical constituents. The comments pertain to toxicity and operational problems (such as corrosion and scaling of pipes) associated with a particular constituent. These concentration ranges, based on a thorough literature search, cover geothermal reservoirs from all parts of the western United States as well as from various other countries with known geothermal reservoirs. It should be noted that the minimum reported concentration for a great majority of the constituents is zero or near zero. Based on the maximum reported concentration (Table 1.3), the chemical constituents in geothermal water can be grouped for convenience under the following categories:

Major constituents - those with maximum concentration greater than 10,000 ppm

Secondary constituents - those with maximum concentration 1,000-10,000 ppm

Minor constituents - those with maximum concentration 1-1,000 ppm

Trace constituents - those with maximum concentration generally less than 0.01 ppm

Table 1.3 presents this grouping of constituents according to their relative abundance. The "major constituents" are those chemicals most commonly found in highest concentration in geothermal systems; they play the most important role in chemical reactions occurring in the system. The "secondary" and "minor" species may also participate significantly in chemical reactions, e.g. scaling and composition. Trace elements contribute very little to the chemical reactions in the system but may have considerable implication in environmental impact. For example,

TABLE 1.1 SOME CHEMICAL INDEX PROPERTIES OF GEOTHERMAL WATERS

Water Characteristics	Reported Range In Geothermal Waters	Reasons for Measurement
TDS	47-387,500 ppm	Measure of material in solution, important in assessing scaling and solid waste problems
pH	∿2-10	Hydrogen ion important to water chemistry and corrosion
Redox Potential	-400 to + 500 mV	Important to water chemistry
Conductivity	500-50,000 μmho/cm	Indication of TDS
Alkalinity	50-1,000 ppm as $CaCO_3$	Ability of water to absorb acid
Hardness	5-20,000 ppm as $CaCO_3$	In general a measure of Ca + Mg
Suspended Solids		Measure of particulates which may clog equipment
Turbidity	0-2,000 Jackson Turbidity Units (JTU)	Estimate of suspended solids

TABLE 1.2 CHEMICAL COMPOSITION OF GEOTHERMAL WATERS WORLDWIDE
(Tsai, et al. in press)

Constituent	Concentration in ppm	Comments
Aluminum (Al)	0 - 7,140	
Ammonium (NH_4)	0 - 1,400	
Arsenic (As)	0 - 12	Health hazard
Barium (Ba)	0 - 250	Human death if >550 mg dosage
Boron (B)	0 - 1,200	Deleterious to plants
(HBO_2)	13.6 - 4,800	
Bromide (Br)	0.1 - 3,080	
Cadmium (Cd)	0 - 1	Toxic to fish if >0.2 ppm
Calcium (Ca)	0 - 62,900	Clogging scale
Carbon Dioxide (CO_2)	0 - 490	Clogging scale
(HCO_3)	0 - 10,150	pH control
(CO_3)	0 - 1,653	
(HCO_3 + CO_3)	20 - 1,000	
(CO_2 + HCO_3 + CO_3)	15 - 7,100	
Cesium (Cs)	0.002 - 22	
Chloride (Cl)	0 - 241,000	Major corrosion constituent
Cobalt (Co)	0.014 - 0.018	Toxic to life in large amounts
Copper (Cu)	0 - 10	Health hazard if >1 ppm
Fluoride (F)	0 - 35	Healthful if <1.5 ppm
Germanium (Ge)	0.037 - 0.068	pH control, corrosion-scale agent
Hydrogen Sulfide (H_2S, total)	0.2 - 74	

(continued)

TABLE 1.2 (continued)

Constituent	Concentration in ppm	Comments
Iodide (I)	0 - 105	
Iron (Fe)	0 - 4,200	May precipitate on oxidation
Lanthanum (La)	20	
Lead (Pb)	0 - 200	Cumulative poison
Lithium (Li)	0 - 300	
Magnesium (Mg)	0 - 39,200	Clogging scale
Manganese (Mn)	0 - 2,000	May precipitate on oxidation
Mercury (Hg)	0 - 10	
Molybdenum (Mo)	0.029- 0.074	
Nickel (Ni)	0.005 - 2	
Nitrate (NO_3)	0 - 35	Drinking standard, 45 ppm
Nitrite (NO_2)	0 - 1	Organic pollutant
Oxygen (O_2, dissolved)	0 - 10	Corrosion-related
Phosphate (PO_4)	0 - 0.3	Eutrophication agent
(HPO_4)	0.75 - 2.05	
(H_2PO_4)	0.02 - 0.22	
Potassium (K)	0.6 - 29,900	Scale-corrosion accelerator
Rubidium (Rb)	0 - 169	
Silica (SiO_2, total)	3 - 1,441	Major scale constituent, corrosion inhibitor
Silver (Ag)	0 - 2	Mandatory limit, 0.05 ppm
Sodium (Na)	2 - 79,800	Scale-corrosion accelerator
Strontium (Sr)	0.133 - 2,000	
Sulfate (SO_4)	0 - 84,000	Clogging scale

(continued)

TABLE 1.2 (continued)

Constituent	Concentration in ppm	Comments
Sulfur (S)	0 - 30	
Total Dissolved Salts	47 - 387,500	
Zinc (Zn)	0.004 - 970	Toxic to fish if > 0.3 ppm
Zirconium (Zr)	24	

The following are trace elements found at Sinclair No. 4 well, Salton Sea, California:

Antimony (Sb), Beryllium (Be), Bismuth (Bi), Cerium (Ce), Dysprosium (Dy), Erbium (Er), Europium (Eu), Gadolinium (Gd), Gallium (Ga), Gold (Au), Hafnium (Hf), Holmium (Ho), Indium (In), Iridium (Ir), Lutetium (Lu), Neodymium (Nd), Niobium (Nb), Osmium (Os), Palladium (Pd), Platinum (Pt), Praseodymium (Pr), Rhenium (Re), Rhodium (Rh), Ruthenium (Ru), Samarium (Sm), Scandium (Sc), Selenium (Se), Tantalum (Ta), Tellurium (Te), Terbium (Tb), Thallium (Tl), Thorium (Th), Thulium (Tm), Titanium (Ti), Tungsten (W), Uranium (U), Vanadium (V), Ytterbium (Yb), Yttrium (Y).

TABLE 1.3 RELATIVE ABUNDANCE OF MAXIMUM REPORTED CONCENTRATIONS OF CHEMICAL COMPOSITION IN GEOTHERMAL WATERS WORLDWIDE (Tsai, et al. in press)

Major Constituents (maximum >100,000 ppm)	Secondary Constituents (maximum 1,000-10,000 ppm)	Minor Constituents (maximum 1-1,000 ppm)	Trace Constituents (maximum <0.01 ppm)	
Chloride	Aluminum	Arsenic	Antimony	Platinum
Sulfate	Iron	Barium	Beryllium	Praseodymium
Sodium	Bromide	Cadmium	Bismuth	Rhenium
Calcium	Manganese	Cesium	Cerium	Rhodium
Magnesium	Strontium	Copper	Dysprosium	Ruthenium
Potassium	Carbonate	Fluoride	Erbium	Samarium
Bicarbonate	Silica (total)	Hydrogen Sulfide(total)	Europium	Scandium
	Ammonium	Iodide	Gadolinium	Selenium
	Boron	Lanthanum	Gallium	Tantalum
		Lead	Germanium	Tellurium
		Lithium	Gold	Terbium
		Mercury	Hafnium	Thallium
		Nickel	Holmium	Thorium
		Nitrate	Indium	Thulium
		Phosphate(total)	Iridium	Titanium
		Rubidium	Lutetium	Tungsten
		Silver	Molybdenum	Uranium
		Zinc	Neodymium	Vanadium
		Zirconium	Niobium	Ytterbium
			Osmium	Yttrium
			Palladium	

secondary and minor constituents such as boron, nickel, zinc, arsenic, rubidium, strontium and barium may be harmful to plant and animal life; most of the heavy metals are involved in formation of scales in pipes.

It is difficult to make a meaningful comparison of the published data on chemistry of geothermal effluents from various parts of the world, because on the one hand the surface and subsurface environments may vary drastically from place to place, and on the other hand the techniques of sampling and analysis of effluents may differ in different reported cases. It is conceivable that some of the data reported in the literature are in error (Ellis, 1976). As the geothermal industry grows and data gathering continues the ranges listed in Table 1.2 will most likely expand.

Usually, low TDS is associated with relatively low concentrations of all constituents, and vice versa. In general, higher temperature waters contain higher concentrations of constituents. Also, the waters with highest salinity appear to have the lowest pH.

The data in Tables 1.1 and 1.2 are biased greatly by the chemical data on the geothermal waters from the Salton Sea KGRA (Imperial Valley, California), where unusually high concentrations of most constituents are common (see Table 2.13). The great majority of the known geothermal reservoirs contain waters with far less TDS than the Salton Sea reservoir.

Because of the inherent diversity in the chemical characteristics of geothermal waters it is difficult to arrive at an average value of concentration of each constituent. As more data become available, statistically significant average and median values of each constituent may be determined, at least for certain geographical areas. The median value of TDS for geothermal water will likely fall in the 1,000 to 10,000 ppm range. Most geothermal fluids appear to be acidic with a pH of less than 7.

With reliable data, chemical composition of geothermal effluents can provide much useful information about the reservoir, since the kinds and amounts of constituents depend on the reservoir environment: formation lithology, rock-water interaction, rock-mineral-chemical equilibria as well as pressure and temperature. The major environmental concerns in a geothermal system are noxious constituents in the effluent. Corrosion in casing, surface plumbing and equipment may cause leakages and consequent contamination of the environment by geothermal fluid; scale formation may make disposal of spent geothermal effluent difficult, and creates a solid waste disposal problem. Chloride, oxygen, sulfide, and pH are principally responsible for corrosion and calcium carbonate scale formation. Silica, sulfide and hydroxide are the other possible scale-forming constituents. Temperature and pressure also play an important role in determining the nature and extent of corrosion and scaling processes. Chemicals may be added to geothermal effluents to reduce possibilities of corrosion and scaling or to precipitate certain constituents in ponds or settling tanks. However, it is conceivable that some of these added chemicals may make the waste geothermal fluid environmentally more detrimental than the reservoir fluid.

Besides the dissolved and suspended solids, geothermal water and steam contain a range of noncondensible gases, some of which may be detrimental to the environment. Hydrogen sulfide, a noncondensible gas constituent of many geothermal fluids, has drawn considerable attention at The Geysers because of its odor. Ammonia, carbon monoxide, sulfur dioxide and mercury vapor are the other major noxious components of many geothermal vapors. Table 1.4 lists the reported concentrations (in volume percent) of most of the known constituents of geothermal vapors (Tsai, et al. in press). The right-hand column in Table 1.4 includes pertinent comments on the environmental implications of these vapor constituents. Usually, noncondensible gases constitute between about 0.3% and 5% of the flashed steam from geothermal fluids (Wood, 1973).

Geothermal fluids usually contain certain radioactive elements in low concentrations, mainly radon, radium and isotopes of uranium and thorium. The most thoroughly studied radioactive element in geothermal fluids is radon-222, a radioactive gas. A study of 136 natural geothermal springs showed a range of 13 to 14,000 picocuries per liter (pCi/l), with a median around 510 pCi/l (O'Connell and Kaufman, 1976).

It is of interest to compare the chemistry of geothermal waters with other types of waters. Figure 1.2 compares the ranges of major chemical constituents in geothermal water and in potable water. In general, the reported maximum concentrations of dissolved constituents in geothermal water exceed those in potable water. The situation is similar when geothermal water is compared with drinking, irrigating, livestock feeding or seawater (Table 1.5).

1.4 ENVIRONMENTAL EFFECTS OF WATER POLLUTANTS

1.4.1 General

Geothermal fluids, if released to surface or groundwater bodies, can potentially cause chemical and thermal effects. This section discusses the environmental effects related to the chemical characteristics and waste heat content of geothermal fluids.

TABLE 1.4

GAS COMPOSITION OF GEOTHERMAL VAPORS (Tsai, et al. in press)

Constituent	Concentration in volume percent	Remarks
Ammonia (NH_3)	0 - 5,36%	Noxious gas, signifies reducing conditions
Argon (Ar)	0 - 6.3	Minor inert gas
Arsenic (As)	0.002 - 0.05	Health hazard, volatile
Boric Acid (H_3BO_3)	0 - 0.45	Deleterious to plants
Carbon Dioxide (CO_2)	0 - 99	Scale formation
Carbon Monoxide (CO)	0 - 3	Health hazard
Helium (He)	0 - 0.3	Innocuous
Hydrocarbon (C_2 and greater)	0 - 18.3	Potential fuel source, denotes reducing conditions
Hydrogen (H_2)	0 - 39	Provides data on oxidation-reduction environment
Hydrogen Fluoride (HF)	0.00002	Extremely corrosive and reactive
Hydrogen Sulfide (H_2S)	0 - 42	Noxious gas, environmental hazard, corrosion agent
($H_2 + H_2S$)	0.2 - 6	
Mercury (Hg)	0.007 - 40.7 (ppb)	Health hazard
Methane (CH_4)	0 - 99.8	Potential fuel source
Nitrogen (N_2)	0 - 97.1	Major inert gas
($N_2 + Ar$)	0.6 - 96.2	
Oxygen (O_2)	0 - 64	Important for oxidation-reduction reactions, can be corrosive
Sulfide Oxides (SO_2)	0 - 31	Corrosion agent, harmful to environment

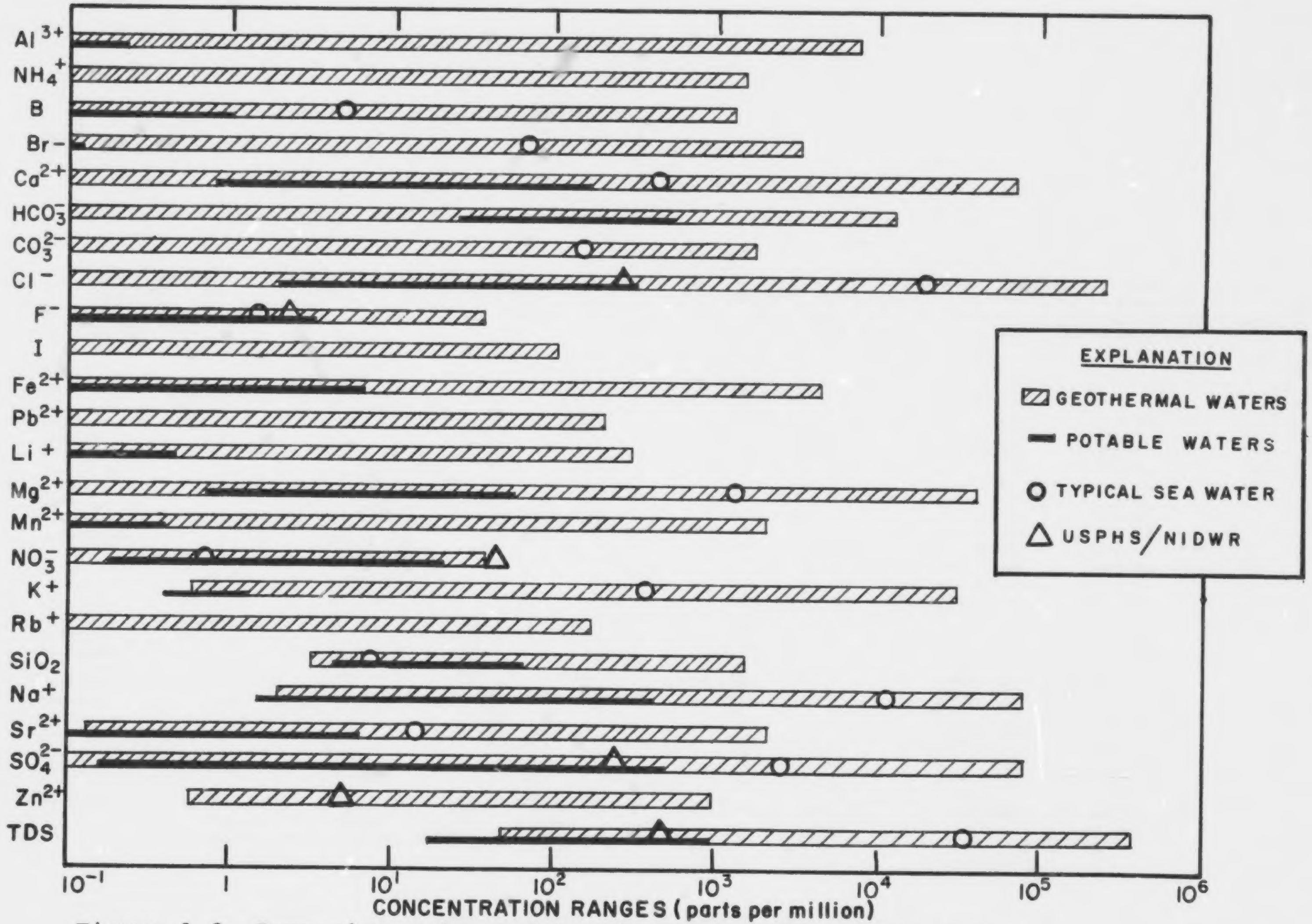


Figure 1.2 Comparison of concentration ranges of constituents in geothermal and potable waters (modified from Tsai, et al. in press)

TABLE 1.5 COMPARISON OF INORGANIC CHEMICAL WATER STANDARDS WITH GEOTHERMAL AND SEAWATER ANALYSES

Substance	Drinking Water[a] (mg/1) USPHS Recommended	Drinking Water[a] (mg/1) USPHS Mandatory	Irrigating Water[b] (ppm) Threshold	Irrigating Water[b] (ppm) Limiting	Livestock Feeding Water[b] (ppm) Threshold	Livestock Feeding Water[b] (ppm) Limiting	Geothermal Water[c] (ppm) Range	Sea Water[d] mg/1
Arsenic	0.01	0.05[g]	1.0	5.0	1	-	0- 12	0.003
Barium	-	1.0[g]	-	-	-	-	0- 250	0.03
Bicarbonate	-	-	-	-	500	500	0- 10,000	142
Boron	-	-	0.5	2	-	-	0- 1,200	4.6
Cadmium	-	0.01[g]	-	-	5	-	0- 1	trace[f]
Calcium		-	-	-	500	1,000	0- 63,000	400
Chloride	250[h]	-	100	350	1,500	3,000	0-240,000	19,000
Chromium	-	0.05[g]	-	-	-	-	-	-
Copper	1.0[h]	-	0.1	1.0	-	-	0- 10	0.003
Fluoride	1.7	2.2	-	-	1	6	0- 35	1.3
Hydrogen Sulfide	-	0.05[h]	-	-	-	-	0.2- 74	-
Iron	0.3[h]	-	-	-	-	-	0- 4,200	0.01
Lead	-	0.05[g]	-	-	-	-	0- 200	trace[f]
Magnesium	-	-	-	-	250	500	0- 39,000	1,350
Manganese	0.05[h]	-	-	-	-	-	0- 2,000	0.002
Mercury	-	0.002[h]	-	-	-	-	0- 10	trace[f]
Nitrate	45	10[g]	-	-	200	400	0- 35	0.5[e]
Selenium	-	0.01[g]	-	-	-	-	trace[f]	0.004
Silver	-	0.05[g]	-	-	-	-	0- 2	trace[f]
Sodium		-	-	-	1,000	2,000	0- 80,000	10,500
Sulfate	250[h]	-	200	1,000	500	1,000	0- 84,000	2,700
Zinc	5[h]	-	-	-	-	-	0- 970	0.01
TDS	500[h]	-	500	1,500	2,500	5,000	47-390,000	34,560
pH	-	6.5-8.5[h]	7.0-8.5	6.0-9.0	6.0-8.5	5.6-9.0	2- 10	-

[a] USPHS, 1962; EPA, 1976; EPA, 1977a

[b] Todd, 1970

[c] Tsai, et al., in press

[d] Goldberg, 1963

[e] Includes NO_2^-, NH_4^+ and dissolved nitrogen gas

[f] Trace=<0.001 ppm (or mg/1)

[g] Maximum contaminant level specified in National Interim Primary Drinking Water Regulations (EPA, 1976)

[h] Maximum contaminant level specified in National Secondary Drinking Water Regulations (EPA, 1977a)

In order to determine if nongeothermal groundwater will be polluted by geothermal groundwater a definition must first be established to distinguish one from the other. The following excerpt exemplifies some of the ambiguity involved in such a definition.

> Strictly defined, any spring [ground] or well water whose average temperature is noticeably above the mean annual temperature of the air at the same locality may be classed as thermal. Among European springs that are developed commercially, only those whose temperature is higher than about 20°C (68°F) are classed as thermal. In the United States, only those springs are called thermal whose temperature is at least 8.3°C (37°F) above the mean annual temperature of the air at their localities. In areas where the mean annual air temperature is low, some springs that do not freeze in winter because of natural protective conditions are considered to be thermal; in tropical areas some springs that are only a few degrees warmer than the temperature of the air may be considered thermal. (Waring, 1965).

Note that these are functional criteria based on temperature. Ideally, a definition of geothermal water would depend on its genesis since it is possible that a water that has come in contact with a geothermal heat source may be relatively cool by the time it reaches the surface. However, it is much more involved to determine water's genesis than to determine its temperature at a collection point. Therefore, a definition based on a somewhat arbitrary temperature differential is used in this report. In Imperial Valley, for example, water hotter than 50°C (122°F) is considered to be geothermal. This rather high figure was selected since geothermal water can be defined relative to ambient air temperatures, and summer air temperatures reach this level in Imperial Valley (Hely and Peck, 1964).

The effects on living things of some of the chemical constituents discussed in section 1.3.3 are not fully known. Even when the effects of a chemical constituent on human, animal or plant health are well known, the actual environmental impact due to that constituent may vary depending on many factors, which include the concentration of that constituent in the geothermal waste fluid, the rate and the cumulative volume of the pollutant released, density of human or animal population in the area, the extent and type of plant life around the pollutant discharge area, and the nature of the discharge area (ocean, lake, river, dry land, subsurface reservoir, etc.). For example, saline discharges to marine waters may be of little consequence while the same discharges may cause a catastrophic impact in a fresh water lake.

Table 1.6 lists the types of Federal-State Water Quality Standards in various states with geothermal potential. The table also indicates whether the criterion for a specific constituent applies statewide or to a designated water. Table 1.5 presents the Drinking Water Standards of the U.S. Public Health Service (USPHS) (1962). It should be noted that limits for many of the chemical constituents of geothermal fluids are not specified in either set of standards.

The following sections summarize the hazards of the various pollutants known to occur in geothermal waters. The hazards are discussed in very general terms as regards human consumption, aquatic life, agricultural and livestock uses, and industrial water supply. The toxicity of the various chemical elements in water has been studied for many years and voluminous literature is available. However, the possible synergistic or antagonistic effects of the combination of various elements in water have received little attention so far.

1.4.2 Human Consumption

Pollution of drinking water supplies is one of the major potential impacts of discharging geothermal wastes into the environment. Of the chemical constituents discussed in section 1.3.3, boron, arsenic, mercury, chromium, antimony, cadmium, selenium, fluoride, lead and nitrate are known to be definitely toxic to human beings, and may cause irreversible damage to human health. Barium, lithium, iodine, bismuth and copper are toxic to a lesser extent and usually do not cause irreversible damage. The USPHS water quality standard specifies limits for arsenic, cadmium, selenium, fluorine, lead, nitrate, barium and copper only (Table 1.5). The National Interim Primary Drinking Water Regulations (1976) (Table 1.5) by EPA specify limits of 0.002 mg/l for mercury and 0.05 mg/l for chromium. The USPHS drinking water standards of 1925 had a recommended limit of 20 mg/l for boron. Neither the 1962 USPHS standards nor the Interim water quality standards (EPA, 1977a) of EPA include boron limits. Several investigators have reported that boron concentrations of 20 to 30 mg/l are not harmful in drinking water, but above this concentration, boron may interfere with digestion (Chen, et al. 1976). There is no limit in the existing federal standards for antimony, lithium, iodine and bismuth. Several other constituents of geothermal water may show minor, usually reversible toxic effects, but significant data are lacking.

1.4.3 Aquatic Life

Table 1.7 is a list of limits suggested for aquatic life in both fresh and marine water. The table also provides remarks on the toxicity of each constituent. Several elements (aluminum,

TABLE 1.6 POLLUTANTS LIMITED BY WATER QUALITY STANDARDS IN STATES WITH GEOTHERMAL POTENTIAL (modified from EPA, 1977b)

	Alaska	Arizona	California	Colorado	Hawaii	Idaho	Louisiana	Montana	Nevada	New Mexico	Oregon	Texas	Utah	Washington	Wyoming
Total Dissolved Solids	d				d		d		d	d	d	d	p		
Chloride							d		s	d	d	d	p		
Iron								d			d		p		
Manganese											d		p		
Boron		d							d		d				
Zinc		d						d			d	s	p		
Barium		d	s								d	s	p		
Fluoride											d		p		
Lead		d	s					d			d	s	p		
Iodine		d						d			d	s	p		
Copper		d						d			d	s	p		
Sulfur															
Arsenic		d	s					d			d	s	p		
Mercury		d	s					d				s			
Chromium		d	s								d	s	p		
Nickel												s			
Silver		d										s	p		
Cadmium		d	s					d			d	s	p		
Selenium		d	s									s	p		
Sulfate							d			d		d	p		
Nitrate (+ nitrite)			s						s				p		
pH (range)	s	d		s	s	s	s	s	s	s	s	s	s	s	
Radioactivity	d	s		s		s	s	d	s		s	s	s	s	s
Total Dissolved Gas						s		s		s	s			s	d
Toxic Materials	d	f		f			s	s	f	s		s		s	f
Temperature	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
Dissolved Oxygen (min.)	s	d		s	s	s	s	d	s	s	s	s	s	s	s
Phosphorus									d	d					
Conductivity										d	d				

d = criteria for designated waters;
s = criteria applied statewide;
p = criteria conform with USPHS Drinking Water Standards, 1962;
f = free from toxic materials.

TABLE 1.7 AQUATIC LIFE CRITERIA FOR CONSTITUENTS IN GEOTHERMAL FLUID (EPA, 1977b)

	Criteria for Fresh water	Criteria for Marine water	Remarks
Ammonia (un-ionized)	0.02 mg/l		Toxicity pH dependent
Arsenic			Daphnia impaired by 4.3 mg/l
Barium			Toxicity level <50 mg/l
Beryllium	0.11 mg/l-(soft water) 1.1 mg/l-(hard water)		Toxicity hardness dependent
Boron			Toxic to minnows at 19,000 mg/l
Cadmium	.004-.0004 mg/l (soft water) .012-.0012 mg/l (hard water)	0.005 mg/l	Toxic at <0.5 mg/l all tests
Chromium	0.1 mg/l		Toxicity varies with pH and oxidation state
Copper	0.1 96-hr LC$_{50}$	0.1 96-hr LC$_{50}$	Toxicity alkalinity dependent
Iron	1.0 mg/l		Toxicity variable
Lead	0.01 96-hr LC$_{50}$ (sol. lead)		Salmonids most sensitive fish
Manganese		0.1 mg/l	Not a problem in fresh water
Mercury	0.0005 mg/l	0.0001 mg/l	High bio-accumulation and thus affects human food
Nitrates			Toxicity to fish > 900 mg/l
Phosphorus		0.0001 mg/l P	Eutrophication factor
Selenium	0.01 96-hr LC$_{50}$	0.01 96-hr LC$_{50}$	Toxic at >2.5 mg/l
Silver	0.01 96-hr LC$_{50}$	0.01 96-hr LC$_{50}$	Toxicity dependent on compound
Hydrogen Sulfide	0.0002 mg/l	0.002 mg/l	Toxic at very low level
Zinc	0.01 96-hr LC$_{50}$		Toxicity dependent on temperature, dissolved oxygen, hardness
Total Dissolved Solids (TDS)			Osmotic effects - variable

bromine, strontium, lithium, cesium, fluorine, rubidium, antimony, nickel and boron), which are known to be toxic to humans are not included in Table 1.7. It is conceivable that these elements are also toxic to aquatic life. Although no criteria are shown for arsenic, barium and boron in Table 1.7, these elements may have toxic effects on aquatic life. Many of these omissions are due to the fact that these elements are not common or are present in insignificant concentrations in surface waters, on which these criteria were based.

The pH of surface waters has been related to productivity, with the most productive waters between pH 6.5 and 8.5. Not only may acids and alkalis be toxic in themselves, but an increase or decrease in pH may raise the toxicity of various constituents, e.g. ammonia.

1.4.4 Agricultural and Livestock Use

Table 1.8 lists the limits suggested on chemical constituents as they pertain to livestock watering and crop irrigation. Remarks on toxicity of each constituent are also included in that table. Again, it should be noted that no limits are suggested in Table 1.8 for many constituents which are known to be toxic to humans. However, Table 1.9 lists minor and trace element tolerances established for irrigation water by the U.S. Department of Agriculture (USDA) in 1962. The concentration of these elements in geothermal waters, as exemplified in Table 1.2, will exceed the USDA guidelines in many cases.

Table 1.5 includes inorganic chemical quality standards for water used in livestock feeding and crop irrigation. Boron is particularly harmful for many plants. Table 1.10 groups common crop plants according to their tolerance of boron into "sensitive", "semi-tolerant" and "tolerant" classes.

1.4.5 Industrial Water Supply

Rather than concentrations of individual constituents, TDS is usually the most important criterion that determines the utility of a water for industrial purposes. Table 1.11 presents the maximum TDS content of surface waters that have been used as industrial waters.

TABLE 1.8 AGRICULTURAL USE CRITERIA FOR CONSTITUENTS IN GEOTHERMAL FLUIDS (EPA, 1977b)

	Crop Irrigation	Remarks
Ammonia		No criteria suggested.
Arsenic	0.1 mg/l	Toxicity to some crops at 0.5 mg/l; no livestock criteria suggested.
Barium		No criteria suggested.
Beryllium	0.001 to 0.500 mg/l	Crop toxicity acidity dependent; no livestock criteria suggested.
Boron	0.75 mg/l	Toxic to sensitive plants, e.g. citrus at <1 mg/l; no livestock criteria suggested.
Cadmium		Reduced crop yields at 1 mg/l; crop accumulation related to zinc concentrations; no livestock criteria suggested.
Chromium		No criteria suggested.
Copper		Toxicity for plants begins at 0.1 mg/l; no livestock criteria suggested.
Iron		No criteria suggested.
Lead		Toxic to plants at <30 mg/l; no criteria suggested.
Manganese	0.2 mg/l suggested for acidophilic crops	Toxicity to plants increases with decreasing pH; no livestock criteria suggested.
Mercury		Bio-accumulation but no criteria suggested.
Nitrates		No criteria suggested; nutrient for crops.

(continued)

TABLE 1.8 (continued)

	Crop Irrigation	Remarks
Phosphorus		No criteria suggested; nutrient for crops.
Selenium		No criteria suggested.
Silver		No criteria suggested.
Hydrogen Sulfide		No criteria suggested.
Zinc		Toxic to some crops at 0.4 to 25 mg/l; may cause iron deficiency in plants; no livestock criteria suggested.
Total Dissolved	500-1,500 mg/l suggested	Osmotic effects in plants; variable harm to both plants and animals.
Sodium		Toxic to certain plants; ratio to other cations important; no criteria given.

TABLE 1.9 MINOR AND TRACE ELEMENT TOLERANCE FOR IRRIGATION WATER (Economic Research Service, 1962)

Element	For Water Used Continuously on All Soils mg/l	For Short-Term Use on Fine Textured Soils Only mg/l
Aluminum	1.0	20.0
Arsenic	1.0	10.0
Beryllium	0.5	1.0
Boron	0.75	2.0
Cadmium	0.005	0.05
Chromium	5.0	20.0
Cobalt	0.2	10.0
Copper	0.2	5.0
Lead	5.0	20.0
Lithium	5.0	5.0
Manganese	2.0	20.0
Molybdenum	0.005	0.05
Nickel	0.5	2.0
Selenium	0.05	0.05
Vanadium	10.0	10.0
Zinc	5.0	10.0

TABLE 1.10 RELATIVE TOLERANCE OF PLANTS TO BORON (USDA, 1954)

Sensitive	Semitolerant	Tolerant
Lemon	Lima bean	Carrot
Grapefruit	Sweetpotato	Lettuce
Avocado	Bell pepper	Cabbage
Orange	Pumpkin	Turnip
Thornless blackberry	Zinnia	Onion
Apricot	Oat	Broadbean
Peach	Milo	Gladiolus
Cherry	Corn	Alfalfa
Persimmon	Wheat	Garden beet
Kadota fig	Barley	Mangel
Grape (Sultanina and Malaga)	Olive	Sugar Beet
Apple	Ragged Robin rose	
Pear	Field pea	Palm (*Phoenix canariensis*)
Plum	Radish	Date palm (*P. dactylifera*)
	Sweet pea	Athel (*Tamarix aphylla*)
American elm		Asparagus
Navy bean	Tomato	
Jerusalem-Artichoke	Pima cotton	
Persian (English) walnut	Acala cotton	
Black walnut	Potato	
Pecan		
	Sunflower (native)	

TABLE 1.11 TDS IN INDUSTRIAL WATERS (EPA, 1977b)

Use	Maximum TDS (mg/l)
Textiles	150
Pulp and Paper	1,080
Chemical	2,500
Petroleum	3,500
Primary Metals	1,500
Copper Mining	2,100
Boiler Make-up	0.5-3,000[a]

[a] From American Society for Testing Materials, 1966.

As discussed in section 1.3.3, TDS in geothermal water varies over a large range, the median being a few thousand ppm. Thus many geothermal waste waters can actually be used as industrial water. Some industrial processes, such as food and beverage processing, may need as high or higher quality water than drinking water in order to maintain consistency of product quality. In such cases, geothermal waste can be a serious pollutant.

1.4.6 Thermal Pollution

Up to 85% of the available heat may be wasted in geothermal electric power generation because of the relative inefficiencies of low temperature conversion. If external once-through cooling water is used, most of this waste heat will be discharged to surface waters. If cooling towers are used, with the cooling water recycled, and blowdown reinjected, most of the waste heat will be dissipated to the surrounding air. Once-through surface water discharges would be particularly detrimental, with large volumes released at temperatures as high as 50°C (122°F). Chemical and heat contamination are likely to be much less in discharges from nonelectric uses of geothermal fluids. One of the principal reasons is that those uses will deal with lower temperature waters which are inherently less saline. Another is that nonelectric systems probably will demand the use of relatively clean water because they will be in more intimate contact with the ultimate energy user.

Waste heat may have particularly significant effects upon aquatic life. Excess heat as expressed by artificial temperature rise or temperature fluctuations can disturb aquatic communities to the extent of complete elimination and replacement. Most water quality standards limit artificially induced stream temperature rise outside a mixing zone to 2.6°C (5°F) or less.

Generally, the standards also include a maximum stream temperature tailored to the preferred temperature of native fish species.

Over many years, continuous thermal pollution may change the microclimate of an area. If extensive geothermal energy development takes place worldwide and thermal pollution from other sources remains unchecked, the possibility of global effects, such as the melting of the polar ice caps or significant change in weather patterns, cannot be ruled out (Axtmann, 1975).

Even if thermal pollution of surface water bodies can be prevented, the microorganisms in soils and porous subsurface rocks may be destroyed by possible excessive thermal pollution outside the reservoir. But the subsurface as a biological habitat is yet to be fully understood (McNabb and Dunlap, 1975). Usually 100°C (212°F) is considered to be the temperature above which bacteria perish, but most micro-organisms are actually killed by temperatures above 50°C (122°F).

REFERENCES

American Society for Testing Materials. First National Meeting on Water Quality Criteria, ASTM Publication No. 4-6, 1966.

Axtmann, R. C. Environmental Impact of A Geothermal Power Plant. Science, v. 187, No. 4179, March 7, 1975.

Chen, J. Y., S. K. Gupta, W. Choi and B. Eichenberger. Chemistry, Fate and Removal of Trace Contaminants from Low to Medium Salinity Geothermal Waste Waters. National Science Foundation Report, November, 1976.

Economic Research Service. Major Uses of Land and Water in the United States. Agriculture Economic Report No. 13, Economic Research Service, U.S. Department of Agriculture, 1962.

Ellis, A. Geothermics - Special Issue, No. 2, p. 516, 1976.

Geonomics. Baseline Geotechnical Data for Four Geothermal Areas in the United States. United States EPA, Environmental Monitoring and Support Laboratory, Las Vegas, Nevada, in press.

Goldberg, E. D. Chemistry - the Oceans as a Chemical System; in Composition of Sea Water, Comparative and Descriptive Oceanography, M. N. Hill, v. 2 of The Sea, New York, Interscience Publications, p. 3-25, 1963.

Hely, A. G. and E. L. Peck. Precipitation, Runoff and Water Loss in the Lower Colorado River-Salton Sea Area. USGS Prof. Paper 486-B, 1964.

McNabb, J. F. and W. J. Dunlap. Subsurface Biological Activity in Relation to Ground-Water Pollution; in Proceedings, Second National Ground Water Quality Symposium, Co-sponsored by U.S. Environmental Protection Agency and the National Water Well Association, Denver, Colorado, 1975.

O'Connell, M. F. and R. F. Kaufman. Radioactivity Associated with Geothermal Waters in the Western United States. Office of Radiation Programs, Las Vegas Facility, Las Vegas, Nevada, Technical Note ORP/LV 75-8A, 25 p., 1976.

Reed, M. J. and G. E. Campbell. Environmental Impact of Development in The Geysers Geothermal Field, U.S.A.; in Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, California, v. 2, p. 1399-1410, 1976.

Sanyal, S. K. Geothermal Reservoirs: Exploration, Development and Assessment. Geothermal Resources Council Short Course, Snowbird, Utah, September, 1976.

Todd, D. K. The Water Encyclopedia, Water Information Center, Port Washington, New York, 559 p., 1970.

Tsai, F., S. Juprasert and S. K. Sanyal. A Review of Chemical Composition of Geothermal Effluents; in Second Workshop on Sampling and Analysis of Geothermal Effluents, February 15-17, 1977, Las Vegas, Nevada. U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Las Vegas, Nevada, in press.

U.S. Department of Agriculture. Handbook 60, 1954.

U.S. Environmental Protection Agency. National Interim Primary Drinking Water Regulations. Office of Water Supply, EPA-570/9-76-003, 159 p., 1976.

________. National Secondary Drinking Water Regulations. 40 CFR Part 143, Federal Register, v. 42, No. 62, p. 17143-17146, Thursday, March 31, 1977a.

________. Quality Criteria for Water. Office of Water and Hazardous Materials, EPA 440/9-76-023, 1977b.

U.S. Public Health Service. Public Health Service Drinking Water Standards. PHS pub. 956, U.S. Govt. Printing Office, 1962.

Waring, G. R. Thermal Springs of the United States and Other Countries of the World - a Summary. USGS Prof. Paper 492, 383 p., 1965.

White, D. E. and D. L. Williams. Assessment of Geothermal Resources of the United States-1975. USGS Circular 726, 155p., 1975

Wood, B. Geothermal Power; in Geothermal Energy Review of Research and Development, ed. by H. C. H. Armstead, UNESCO, Paris, 1973.

SECTION TWO

IMPERIAL VALLEY

2.1 INTRODUCTION

This section discusses the potential subsurface environmental impact in geothermal areas of Imperial Valley (Figs. 2.1 and 2.2) with emphasis on potential water pollution. First background information is presented, followed by discussions of the geothermal system, potential water pollution, seismicity, subsidence and pollution control technology currently practiced or anticipated.

The following discussions on the geothermal systems and water pollution are divided into five subsections, one each on the major potentially developable geothermal resources at the Salton Sea, East Mesa, Heber and Brawley KGRAs and one section on the remaining KGRAs in the valley. It was not advantageous to divide the summary of Imperial Valley geotechnical data, seismicity, subsidence and pollution control technology sections into geographic subsections.

2.1.1 Summary

There are six "Known Geothermal Resource Areas" (KGRAs) in Imperial Valley (Fig. 2.2). The East Mesa, Salton Sea, Heber and Brawley KGRAs are considered potentially suitable for electric power production. Electric power production test facilities are operating or are planned for the East Mesa, Salton Sea and Heber areas. The geothermal well effluents at East Mesa average from 2,000 to 3,000 ppm TDS, at Salton Sea 200,000 ppm TDS, at Heber 15,000 ppm TDS, and at Brawley 100,000 ppm TDS. The trace element contents of these brines are generally directly proportional to the TDS contents, i.e. the higher the TDS the higher the content of each trace element.

Based on various assumptions, approximations and extrapolations, the estimates of the recoverable heat in Imperial Valley range from 20×10^{18} to 200×10^{18} J (1.9×10^{16} to $1.9\ 10^{17}$ BTU). The 30-year electric power potential for Imperial Valley is estimated at 4,590 megawatts (electricity) (MWe). It is estimated that a total brine mass of 6.02 million kg/day (13.29 million lb/day) will be produced from this projected

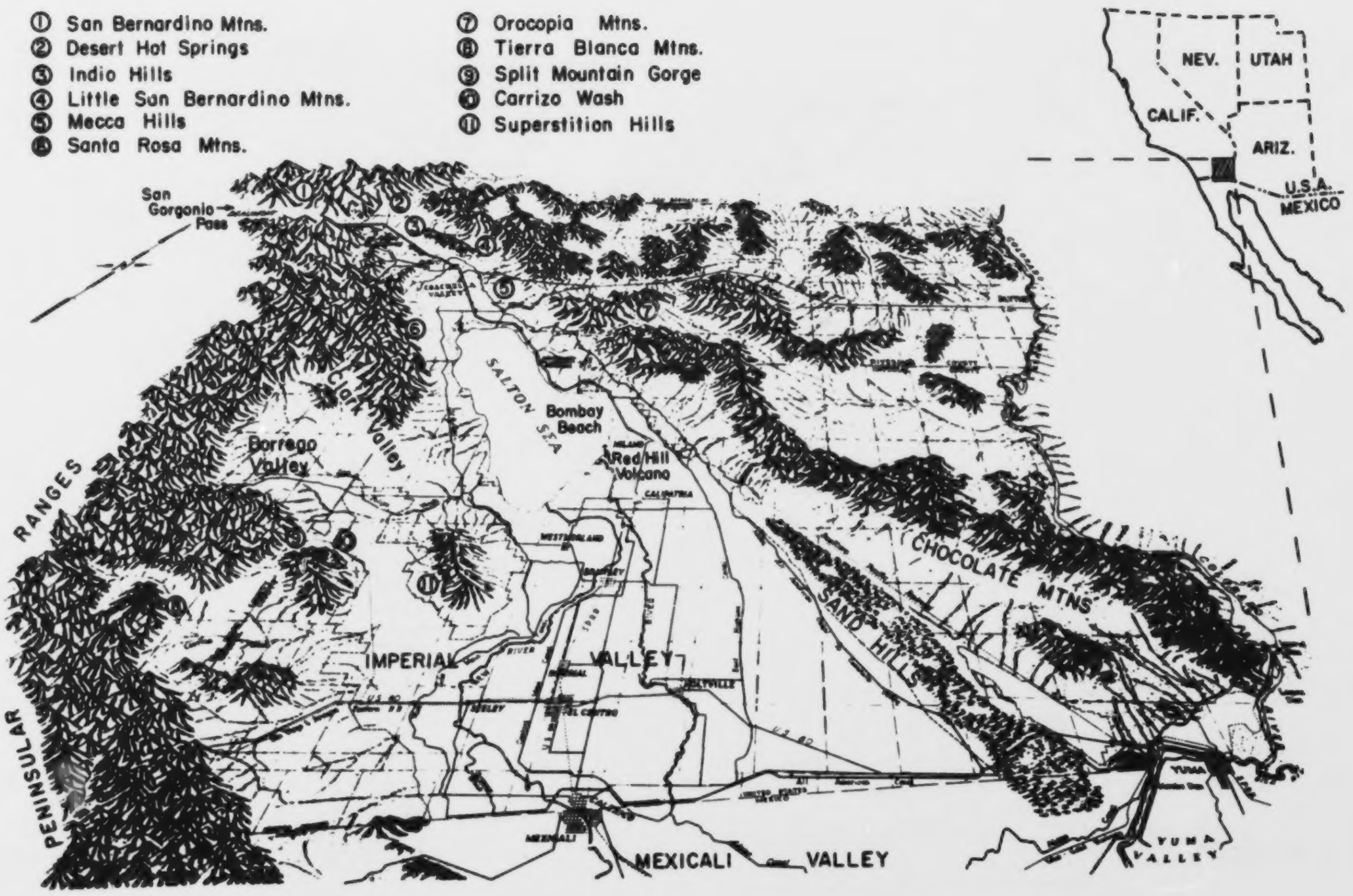

① San Bernardino Mtns.
② Desert Hot Springs
③ Indio Hills
④ Little San Bernardino Mtns.
⑤ Mecca Hills
⑥ Santa Rosa Mtns.
⑦ Orocopia Mtns.
⑧ Tierra Blanca Mtns.
⑨ Split Mountain Gorge
⑩ Carrizo Wash
⑪ Superstition Hills
NEV.
UTAH
CALIF.
ARIZ.
U.S.A.
MEXICO
San Gorgonio Pass
SALTON SEA
Bombay Beach
Red Hill Volcano
Borrego Valley
Clark Valley
RANGES
PENINSULAR
IMPERIAL
VALLEY
CHOCOLATE MTNS
SAND HILLS
MEXICALI
VALLEY
YUMA
YUMA VALLEY

Figure 2.1 Physiographic setting and location of Imperial Valley, California (Coplen, 1976)

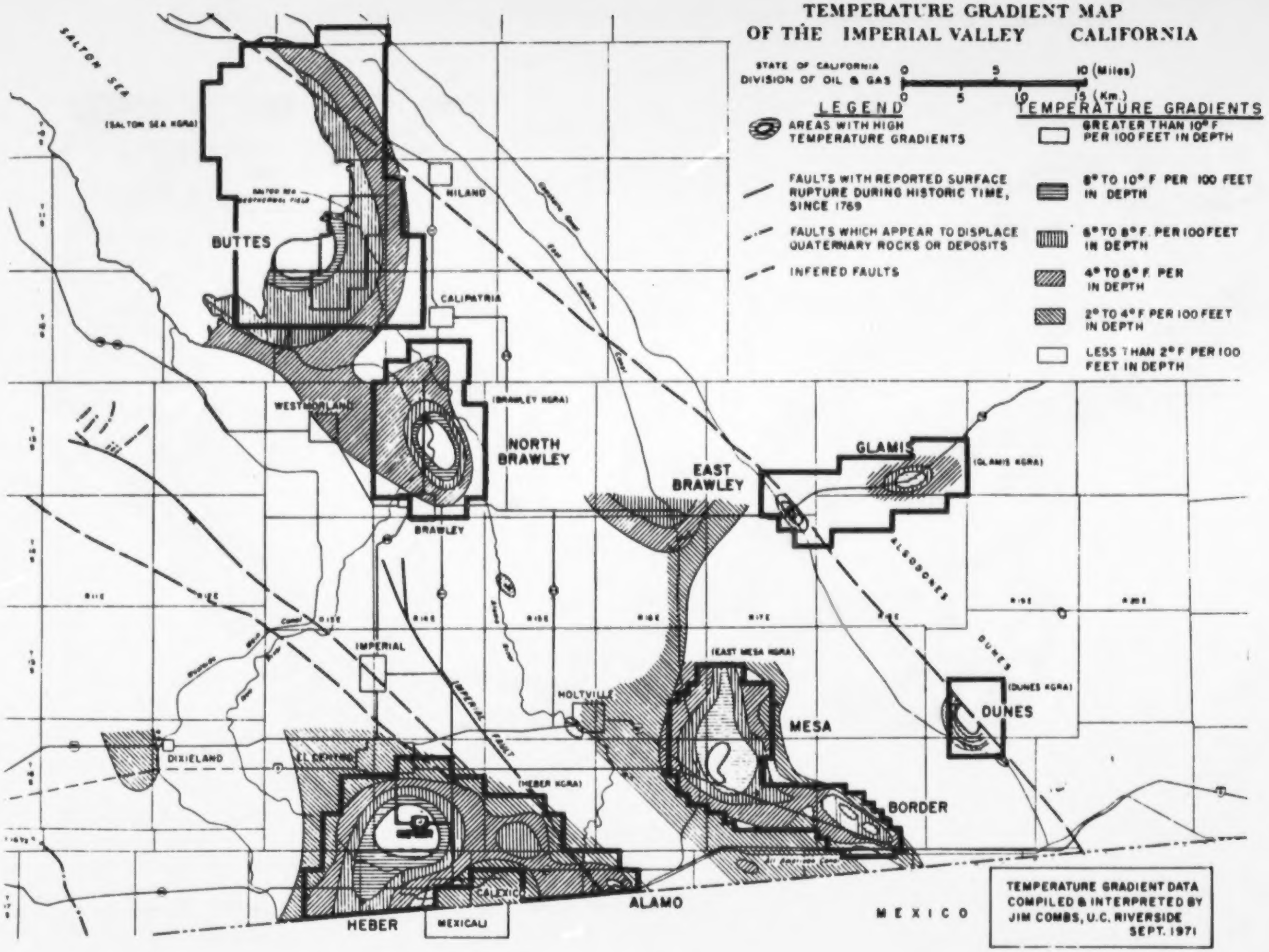

TEMPERATURE GRADIENT MAP
OF THE IMPERIAL VALLEY CALIFORNIA
STATE OF CALIFORNIA
DIVISION OF OIL & GAS
0 5 10 (Miles)
0 5 10 15 (Km.)
LEGEND
AREAS WITH HIGH TEMPERATURE GRADIENTS
FAULTS WITH REPORTED SURFACE RUPTURE DURING HISTORIC TIME, SINCE 1769
FAULTS WHICH APPEAR TO DISPLACE QUATERNARY ROCKS OR DEPOSITS
INFERED FAULTS
TEMPERATURE GRADIENTS
GREATER THAN 10° F PER 100 FEET IN DEPTH
8° TO 10° F PER 100 FEET IN DEPTH
6° TO 8° F. PER 100 FEET IN DEPTH
4° TO 6° F. PER IN DEPTH
2° TO 4° F PER 100 FEET IN DEPTH
LESS THAN 2° F PER 100 FEET IN DEPTH
SALTON SEA
(SALTON SEA KGRA)
SALTON SEA GEOTHERMAL FIELD
BUTTES
NILAND
CALIPATRIA
WESTMORLAND
(BRAWLEY KGRA)
NORTH BRAWLEY
BRAWLEY
EAST BRAWLEY
GLAMIS
(GLAMIS KGRA)
ALGODONES
DUNES
(DUNES KGRA)
IMPERIAL
IMPERIAL FAULT
HOLTVILLE
(EAST MESA KGRA)
MESA
BORDER
DIXIELAND
EL CENTRO
(HEBER KGRA)
HEBER
CALEXICO
MEXICALI
ALAMO
MEXICO
TEMPERATURE GRADIENT DATA COMPILED & INTERPRETED BY JIM COMBS, U.C. RIVERSIDE SEPT. 1971

Figure 2.2 Temperature gradient map showing locations of KGRAs in Imperial Valley, California (Palmer, 1975)

maximum power development and will contain from 345,000 to 391,000 kg (760,000 to 862,000 lb) TDS. This mass of hot brine and its contained solids will constitute the major potential source of subsurface pollution due to geothermal development in Imperial Valley. If the spent geothermal fluids are allowed to escape into surface water bodies or very shallow aquifers, considerable thermal pollution may result in addition to chemical pollution.

For Imperial Valley the major pollution control technology envisioned is injection of spent fluids into the producing formation. This technology may affect natural groundwater conditions, seismicity and subsidence. A preliminary compilation of wells and well use in Imperial Valley disclosed very limited groundwater use in the KGRAs, (or limited use in non-geothermal groundwater aquifers up-gradient from potential geothermal development).

Imperial Valley is a region of high seismicity and significant tectonic movement. Descriptions and preliminary data are presented here describing seismicity and subsidence monitoring networks. These networks will provide extensive baseline data to aid in distinguishing the high levels of naturally occurring seismicity and subsidence from that potentially induced by future geothermal development.

2.1.2 Background

Numerous studies are being conducted to evaluate and utilize the geothermal potential of Imperial Valley. The first geothermal well was drilled in 1927 near fumaroles and mud pots by the southern shore of the Salton Sea. The steam from this well, although not of sufficient quality or quantity for power production, contained carbon dioxide gas and was utilized from 1934 to 1954 to produce dry ice. In 1957, a wildcat oil well encountered 315°C (600°F) brine at a depth of 1,430 m (4,700 ft) about 8 km (5 mi) south of the previously explored area. In 1968, the U.S. Bureau of Reclamation (USBR) began funding Imperial Valley geothermal exploration studies through the University of California at Riverside (U.C.R.). These studies involved gravity, resistivity, magnetic and temperature gradient surveys and they identified eight areas with temperature gradients greater than 3.6°C per 100 m (2°F per 100 ft) of depth. Six of these areas are currently designated as KGRAs and four of them are considered to have geothermal power production potential.

The Brawley and Heber KGRAs, the westernmost portion of the East Mesa KGRA, and the landward portion of the Salton Sea KGRA lie within irrigated agricultural land, roughly defined by the area between the East Highline and Westside Main Canals (Fig. 2.2). Presently, 103,125 ha (254,827 acres) are designated as KGRAs. This represents about one-tenth of the land area of

Imperial County. Of the 192,000 ha (475,000 acres) of irrigated agricultural land in Imperial Valley about 57,000 ha (140,000 acres) or approximately one-third is included in designated KGRAs.

The climatology, baseline chemical characteristics of water, geology, hydrology, and historic seismicity of Imperial Valley are discussed in detail in "Baseline Geotechnical Data for Four Geothermal Areas in the United States" (Geonomics, in press) and are summarized below.

2.1.3 Summary of Imperial Valley Geotechnical Data

The Salton Trough is an area of high regional heat flow and contains numerous geothermal anomalies (Fig. 2.2) (Combs, 1971). It is one of the most seismically active areas in the United States and significant subsidence rates have been measured. Geologic evidence shows that the trough has experienced intensive crustal deformation, active faulting (Richter, 1958; Allen, et al. 1965; Brune and Allen, 1967), and subsidence (Elders, et al. 1972), and that deformation is currently continuing.

The Imperial Valley is a hot, naturally arid area with a mean annual precipitation of less than 80 mm (3 in.). It is a relatively flat alluvial valley with the central portion heavily irrigated. The valley is a broad structural and topographic depression that has been filled with over 6,000 m (20,000 ft) of later Tertiary deltaic and lacustrine sands, silts and gravels overlain by alluvium and lake sediments. The underlying pre-Tertiary granitic and metamorphic complex is intensely step-faulted down from the mountains on both sides of the valley.

The combination of graphic chemical-analytic representations presented in Geonomics (in press) provides an effective basis for establishing baseline water quality parameters in Imperial Valley. Three depth zones were defined based on perforated well intervals. They are shallow, from 24 to 91 m (80 to 300 ft); intermediate, from 91 to 457 m (300 to 1,500 ft); and deep, more than 457 m (1,500 ft). Modified Stiff diagrams aided in defining the areal and depth distribution of five water types in Imperial Valley. These are a sodium chloride water, a high sulfate water, a sodium chloride with high calcium water, a sodium chloride with high sulfate and/or magnesium water and a sodium bicarbonate water. The Stiff diagrams depict the great variation in the chemical characteristics of groundwater throughout the valley, from the purest waters coming off the Peninsular Range to the hypersaline brines occurring in the Salton Sea geothermal area. A salinity gradient exists from the southeastern end of the valley with salinity increasing to the west and north as well as with depth.

The geology of the Imperial Valley is complicated with myriad fault traces and thousands of meters of discontinuous, folded and layered sediments. The San Andreas, San Jacinto, Elsinore and Salton Trough Fault Zones are all components of the San Andreas System that fractures the sediments and basement of the valley. A detailed compilation of these faults has been prepared (Geonomics, in press) and many fault traces have been located in each of these fault zones. Many other concealed traces in alluvial areas remain to be discovered with further detailed investigation. The Salton Trough Fault Zone has been defined as a unique zone, containing parallel, subparallel and orthogonal fault traces between the San Andreas and San Jacinto Fault Zones. Most of the faults in this zone are concealed and have been inferred from geophysical evidence (Meidav, et al. 1976).

Rocks in the Salton Trough range in age from Precambrian basement complex to Recent alluvium and dune sands, and correspondingly from dense, competent hard rocks to totally unconsolidated sedimentary deposits and young volcanics. Most of the central valley is Pliocene and younger. One deep well near Brawley intercepted over 4,000 m (13,000 ft) of interbedded fine grained sandstone and siltstone. The main source of the thick section of Eocene to Holocene nonmarine sediments has been Colorado Plateau debris transported by the Colorado River, with some contribution from local sources. Tertiary volcanic and intrusive rocks occur within the sedimentary section.

Imperial Valley groundwater generally flows northward and westward as underflow from the Colorado River, canal leakage and irrigation discharge. This flow is generally distributed into shallow and deep water bearing strata. Flow pattern complications arise from the presence of faults and stratigraphic aquitards which channel and restrict water flow. It is conjectured that local convective patterns tend to cause regional waters to flow radially inward towards the geothermal anomalies. All water is discharged from the closed Salton Sea drainage basin through evaporation and evapotranspiration.

The flow rate of wells is quite variable throughout the valley, from over 3,800 lpm (1,000 gpm) in a shallow well in the southeastern valley to essentially nil in some shallow wells in the central portion. However, deep wells in the central valley flow as well or better than wells at the valley margins (Loeltz, et al. 1975).

The total volume of water in storage has been estimated between 0.20 and 0.59 billion ha-m (1.6 and 4.8 billion acre-ft) (Rex, 1970), with another estimate of 0.97 billion ha-m (8.0 billion acre-ft) of usable and recoverable water in storage (Dutcher, et al. 1972).

Artificially induced recharge of Imperial Valley groundwater from canal leakage and irrigation applications has notably raised groundwater levels, especially in the southeastern portion of the valley.

Seismic activity is widespread and abundant in Imperial Valley. Nine earthquakes of magnitude 6.7 or greater have occurred in the Imperial-Coachella Valley area since 1850; the Imperial Valley earthquake of 1940 was the most significant event in terms of human disturbance. It has been difficult to correlate much of the historic seismicity with active faults, correlation of microseismicity with active faults has been more fruitful.

Microearthquake activity is sometimes associated with geothermal anomalies, and its occurrence may increase with geothermal development or injection of geothermal fluids. A number of microseismic monitoring networks have been installed in Imperial Valley by the U.S. Geological Survey (USGS), California Institute of Technology (Cal Tech), and Chevron Oil Company. Changes in earthquake recurrence statistics and/or in the depth and location of events from pre-production activity may be used to detect production-induced seismicity.

Two reports on environmental impact of geothermal development in Imperial Valley, which cover aspects complementary to those covered in this report, have been published recently by the Imperial Valley Environmental Project of Lawrence Livermore Laboratory (LLL). These reports include:

> "A Description of Imperial Valley, California for the Assessment of Impacts of Geothermal Energy Development"; D. Layton and D. Ermak; August 26, 1976.
>
> "Imperial Valley Environmental Project: Progress Report"; P.L. Phelps and L.R. Anspaugh, eds.; October 19, 1976.

The following report on the geotechnical aspects of the environmental impact of geothermal development in the Heber KGRA has been published by the Electric Power Research Institute of Palo Alto:

> "Some Geotechnical Environmental Aspects of Geothermal Power Generation at Heber, Imperial Valley, California"; Geonomics, Inc.; EPRI ER-299; October, 1976a.

2.2 GEOTHERMAL SYSTEMS

There are at least seven geothermal systems in the Salton Trough structural province. One is located at Cerro Prieto, Mexico and the remaining six are in Imperial Valley. All of these systems are intermediate to high temperature hot water systems with salinities ranging from over 1,000 ppm in the Dunes and East Mesa KGRAs to 385,000 ppm in the Salton Sea KGRA. Fluid temperatures range from 135°C (275°F) for the low salinity fluid to 340°C (644°F) for the hypersaline brine. A knowledge of the quantity of the resource is pertinent in assessing environmental impact in order to estimate the amount of fluids and chemical constituents that will potentially be produced. The following discussion is largely extracted from Ermak and Buchanan (1976), who have recently summarized the geothermal resource of Imperial Valley.

Estimation of the geothermal resource of Imperial Valley is difficult at this time due to the lack of factual data on actual reservoir temperatures, volume, heat capacity and water-to-rock ratios for all but a small percentage of the potential resource. Since only about 5% of the potential resource has been proven by drilling (Towse, 1975) many assumptions must be made to estimate it. Previous estimates have ranged over five orders of magnitude (Anderson and Axtell, 1971; Combs, 1971; Dutcher, et al. 1972; Helgeson, 1968; Rex, 1970), but more recent investigations have narrowed the discrepancy to one order of magnitude (Towse, 1975; Renner, et al. 1975; Biehler and Lee, 1977; Nathenson and Muffler, 1975). These current potential geothermal resource estimates, each utilizing different methods and assumptions of reservoir properties, are summarized in Table 2.1 and are discussed below.

Renner, et al. (1975) estimated a reservoir depth of 3,000 m (10,000 ft), considered only fluids with temperatures above 150°C (302°F) and assumed a volumetric specific heat of 0.6 cal/cm^3-°C to arrive at a total estimated stored heat of 175 x 10^{18} joules (J) (1.66 x 10^{17} BTU) for the Salton Trough. Nathenson and Muffler (1975), in their assessment of electric power generation potential, assumed that 25% of the Renner, et al. (1975) stored heat would be recoverable for an estimated total of 43.7 x 10^{18} J (4.14 x 10^{16} BTU). Towse (1975) defined the geothermal reservoir volume from a temperature gradient map (Combs, 1971), assuming that usable geothermal fluid extended to whichever was less, 300 m (1,000 ft) below the 230°C (446°F) isotherm or a maximum depth of 2,100 m (7,000 ft). He estimated that 59% of the reservoir would be composed of permeable sandstone with a specific yield of 0.16 (Dutcher, et al. 1972). The water enthalpy was estimated at .590 x 10^6 J/kg (560 BTU/lb) and the specific gravity of the water at 1.0. Towse states that specifying other reservoir properties could increase the total recoverable heat estimate of 20 x 10^{18} J (1.9 x 10^{16} BTU) by as much as 150%.

Biehler and Lee (1977) estimate the heat stored in the recoverable fluid from "excess mass" calculations based on gravity anomalies. The reservoir volume is computed by dividing

TABLE 2.1 ESTIMATES OF STORED AND RECOVERABLE HEAT IN THE GEOTHERMAL RESOURCES OF IMPERIAL VALLEY

	Total Stored Heat in Rock and Water	Heat in Recoverable Fluid (All values in 10^{18} J)			
	a	b	c	d	e
Salton Sea	87.9	22.0	11.0	35.4 to 106.1	14.1
Heber	46.0	11.5	3.5	8.3 to 25.0	7.4
East Mesa	23.0	5.8	3.0	10.4 to 31.2	3.7
Brawley	12.6	3.2	1.0	13.2 to 39.6	2.0
Glamis	1.7	.4	1.0	-	0.3
Dunes	2.5	.6	0.5	0.06 to 0.2	0.4
E. Brawley	0.8	.2	-	-	0.1
TOTAL	174.5	43.7	20.0	67.4 to 202.1	28.0

[a] Renner, et al. (1975)
[b] Modified from Nathenson and Muffler (1975), based on Renner, et al. (1975) and using a thermal energy recovery factor of 0.25
[c] Towse (1975) and Ermak and Buchanan (1976)
[d] Biehler and Lee (1977)
[e] Based on Renner, et al. (1975) and using a thermal energy recovery factor of 0.16 (see text for explanation)

the total "excess mass" by the density contrast. The reservoir volume will vary depending on what density contrast is assumed between different masses. Biehler and Lee (1977) provide a range of estimates based on possible density contrasts of 0.1 g/cc (6 lbs/ft^3), 0.2 g/cc (12 lbs/ft^3), and 0.3 g/cc (19 lbs/ft^3), an average porosity of 20%, an average yield of 80%, a fluid density of 1 g/cc (62.43 lbs/ft^3) and a fluid enthalpy of .590 x 10^6 J/kg (560 BTU/lb). This approximation provides a range of estimates from 67.4 to 202 x 10^{18} J (6.38 x 10^{16} to 20 x 10^{17} BTU) for the heat content in the recoverable fluid, which is much higher than the Towse (1975) or Nathenson and Muffler (1975) estimates. The upper limit is even higher than the total stored heat in the rock and fluid in the Imperial Valley estimated by Renner, et al. (1975).

Another estimate of the recoverable heat resource for Imperial Valley is proposed here. In this estimation, the total resource estimate of Renner, et al. (1975) is accepted and an area specific recovery factor (the amount of recoverable fluid in the reservoir) is applied to it. This is similar to the approach of Nathenson and Muffler (1975), but instead of using the general recovery factor which they applied to all geothermal areas in the United States, a recovery factor based on the physical properties of the reservoirs is used. This recovery factor uses an average porosity value of 20% and an average yield of 80% (Biehler and Lee, 1977) for an average recovery factor of 0.16. Using these figures, the heat in storage in the recoverable fluid is 28.0 x 10^{18} J (2.65 x 10^{16} BTU) for the entire Imperial Valley. This estimate is nearly midway between the Towse (1975) and Nathenson and Muffler (1975) estimates. However, this estimate does not account for a dynamic hydrologic system, where both natural recharge and injection of geothermal waste water can take place. Both natural recharge and injection will increase the amount of total energy recovered from the reservoir.

It is important to consider that the Renner, et al. (1975) estimate is for the total heat contained in the rock and water while the Nathenson and Muffler (1975), Towse (1975) and Biehler and Lee (1977) estimates are for the potentially recoverable resource.

All investigators agree that the Salton Sea geothermal field contains the major portion of the resource, with Renner, et al. (1975) estimating it as 50%, Towse (1975) as 50% and Biehler and Lee (1977) as 40%. It is apparent from these studies that considering the current state of technology, only the Salton Sea, East Mesa, Heber and Brawley fields contain commercial quality and quantity of geothermal water.

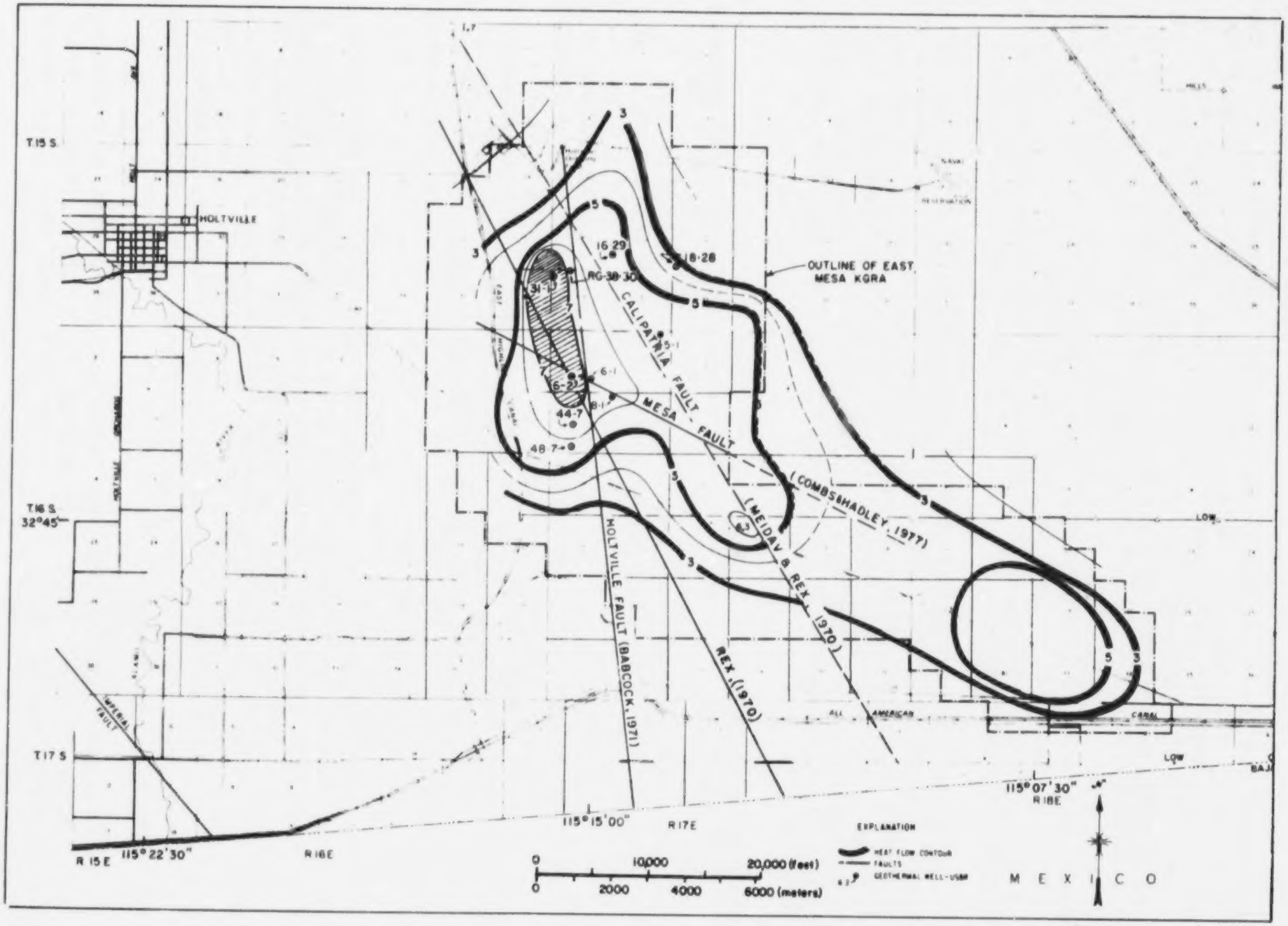
Descriptions of the individual geothermal fields are outlined below.

2.2.1 East Mesa KGRA

High temperature gradients, relatively low salinity fluids and a thick section of fluid saturated rock make the East Mesa geothermal field an attractive area for potential geothermal energy development. The sedimentary rocks and sediments are relatively flat-lying (Randall, 1974) and difficult to correlate. Vertical groundwater flow is limited by the lenticular nature of the more impermeable sediments (Black, 1975). The fluid is assumed to flow via fractures in the deeper, more brittle rocks (U.S. Bureau of Reclamation, 1971). This assumption is supported by core samples from the deep production zone at 2,250 m (7,400 ft) in Mesa 6-1, which consists of well-cemented sandstone of low intergranular permeability. Core samples from a depth of 2,133 m (7,000 ft), 120 m (400 ft) above the sandstone, contain shale with slickensides and calcite-filled fractures.

Randall's (1971) correlations show that the surficial deposits are underlain by a thick wedge of sandstone, up to 3,700 m (12,000 ft) thick (Biehler, et al. 1964). The sandstone is derived from the coarser deposits of the Colorado River Delta and from windblown sand. This is corroborated by sand grain surface features on drill cuttings indicating the origin as dune sand, dune plain sand and dune sand reworked during lacustrine processes (Rex, et al. 1971).

The Mesa anomaly exhibits high thermal gradients (Combs, 1971), low resistivity (Meidav and Furgerson, 1972), seismic noise, microearthquake activity at depth (U. S. Bureau of Reclamation 1974), and a positive gravity anomaly (Biehler, 1971). The low resistivity is indicative of either high salinity or high temperature water or both. The positive gravity anomaly is indicative of more dense rock. From calculations based on this gravity data, Biehler (1971) and Meidav, et al. (1975) hypothesized that the density contrast is mostly within the sedimentary section, and is a result of silica or calcium carbonate deposition in the interstitial pore spaces of the sandstone. Silica would be precipitated as the hot geothermal fluids rise and cool. Calcium carbonate would be precipitated if calcium carbonate-rich cooler water is heated as it mixes with hotter geothermal brine. However, no siliceous cap rock, such as has been discovered in East Mesa, can be found in the nearby Dunes area (Coplen and Kolesar, 1974; Combs, 1972). Black (1975) proposes that the higher density mass in the area must be caused by the presence of an igneous intrusion at depth, or by higher density thermally metamorphosed rocks resulting from rising geothermal fluids. The absence of a magnetic anomaly suggests that there is no igneous intrusion and thereby tends to support the thermal metamorphosis explanation of the gravity anomaly.



T.15 S.
HOLTVILLE
T.16 S.
32°45'
T.17 S.
IMPERIAL FAULT
R 15 E
115°22'30"
R16E
115°15'00"
R17E
115°07'30"
R18E
OUTLINE OF EAST MESA KGRA
16-29
18-28
RG-38-30
31-1
5-1
6-1
6-2
8-1
44-7
48-7
CALIPATRIA FAULT
MESA FAULT
(COMBS&HADLEY, 1977)
(MEIDAV & REX, 1970)
REX, (1970)
HOLTVILLE FAULT (BABCOCK, 1971)
3
5
ALL AMERICAN CANAL
EAST HIGHLINE CANAL
LOW
0
10,000
20,000 (feet)
0
2000
4000
6000 (meters)
EXPLANATION
HEAT FLOW CONTOUR
FAULTS
GEOTHERMAL WELL-USBR
M E X I C O

Figure 2.3 Geothermal well locations, heat flow contours, and mapped faults, East Mesa KGRA (modified from U.S. Bureau of Reclamation, 1974)

Four faults have been mapped on the Mesa anomaly since 1970 (Fig. 2.3). Typical of faults in the alluvial parts of Imperial Valley, all of these faults have been identified by geophysical techniques and none of them has surface expression. The Calipatria Fault (Meidav and Rex, 1970) location was based on an electrical resistivity survey; however the control in the southern part of the survey was poor and the location of the fault through the East Mesa geothermal field is quite conjectural. The unnamed fault cited by Rex (1970) and U.S. Bureau of Reclamation (1974) is, in fact, the Calipatria Fault. The Mesa Fault (Combs and Hadley, 1977) has been located by a microseismic monitoring network. The Holtville Fault (Babcock, 1971) has been located by aerial and infrared photography and its actual existence is uncertain.

Some or all of these faults may allow upward flow of geothermal fluid, thereby controlling the location of the East Mesa geothermal anomaly. However, faults may be aquitards as well as conduits. Though the fault itself may not function as the actual conduit, a fracture zone associated with the inferred faults is postulated as the vertical conduit for the geothermal fluids (Black, 1975).

Resource Base and Production Potential--

The resource base at East Mesa has been estimated by Renner, et al. (1975) at 2.30×10^{19} J (2.18×10^{16} BTU). Of this total stored heat in the water and rock, estimates of the heat content in the recoverable fluid range from 3.0×10^{18} J (2.8×10^{15} BTU) (Towse, 1975) to 3.12×10^{19} J (2.96×10^{16} BTU) (Biehler and Lee, 1977). For this field, the Biehler and Lee (1977) maximum estimate of heat content in the recoverable fluid is greater than the Renner, et al. (1975) estimate for the total heat in storage in the rock and fluid. If we accept the Renner, et al. (1975) value for the total heat and apply the 0.16 recovery factor (described in section 2.2), the heat in the recoverable fluid is estimated as 3.7×10^{18} J (3.5×10^{15} BTU) for the East Mesa area.

The Mesa anomaly was chosen by the USBR as the site for five geothermal test wells, all drilled to depths greater than 1,800 m (6,000 ft). The locations of these wells were based on the results of geophysical surveys and they were drilled between August 1972 and June 1974. Casing and completion data for these wells, named Mesa 6-1, 6-2, 5-1, 8-1 and 31-1, are given in Table 2.2. This table includes casing outside diameters and depths, slotted and perforated intervals, and average Saraband sand permeability index.

Flow rates and pressures were measured for all the wells except Mesa 31-1. Fig. 2.4 shows flow rate versus wellhead gauge pressure for Mesa 6-1, 6-2, 5-1 and 8-1. As would be expected, the flow rate for these wells decreases as the well-

TABLE 2.2 CASING AND COMPLETION RECORDS, EAST MESA TEST SITE
(Mathias, 1975)

Mesa+ well number	Casing outside diameter (in.)	Kelly* bushing elevation (m above msl)	Depth interval (m)	Slotted interval (m)	Perforated interval (m)	Average Saraband sand permeability (md)
6-1	20	18	0-116			
	13 3/8		0-763			
	9 5/8		0-223		2075-2179	230
	7		2213-2443	2238-2433		1.5
6-2	20	12	0-19			
	11 3/4		0-301			
	7 5/8		0-1816	1663-1816		70
5-1	20	15	0-18			
	13 3/8		0-312			
	7 5/8		0-1830	1525-1830		69
8-1	20	20	0-18			
	13 3/8		0-304			
	7 5/8		0-1829	1508-1829		39
31-1	20	16	0-18			
	13 3/8		0-309			
	7 5/8		0-1882	1652-1882		62

+Well locations shown on Figure 2.9.

*From Black, 1975
All Kelly bushings are about 5 m above ground surface, except Mesa 6-1 which is about 7 m above ground surface. (U.S. Bureau of Reclamation)

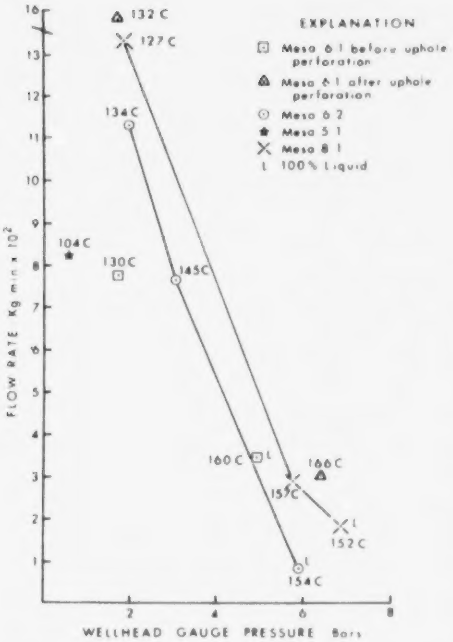


Figure 2.4 Pressures, temperatures and total flow rates, Mesa 6-1, Mesa 6-2, Mesa 5-1 and Mesa 8-1 (Mathias, 1975)

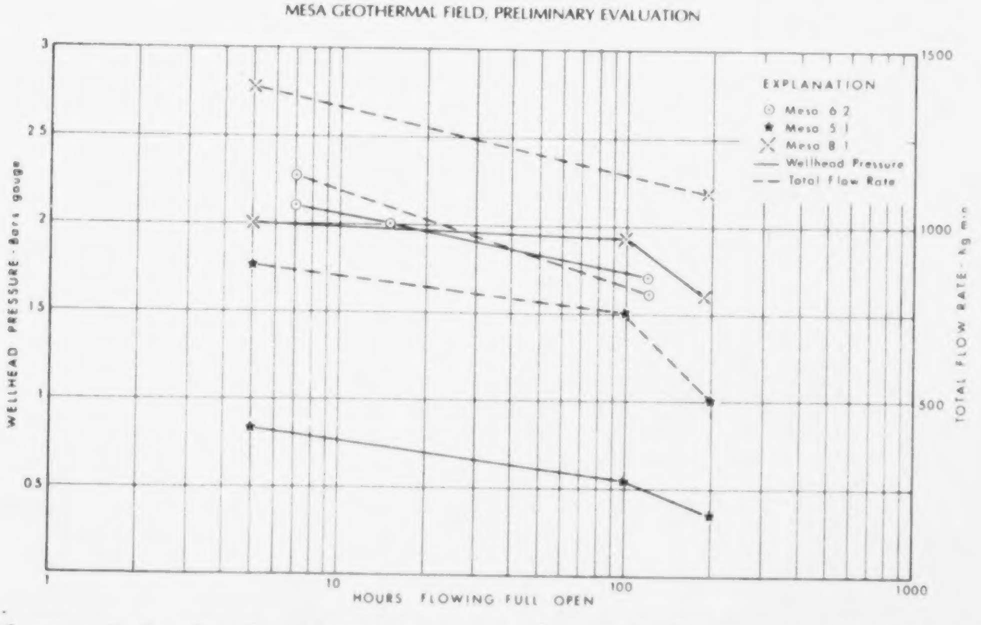


Figure 2.5 Surface pressures and total flows, wells flowing full open, Mesa 6-2, Mesa 5-1 and Mesa 8-1 (Mathias, 1975)

head pressure is increased. These flows are representative of rates occurring after several days of well operation and were recorded after 24 to 48 hours of stabilized flow. The only equilibrium condition at the lower flow rates was reached at well 6-1 after uphole perforation.

In Mesa 6-1, after reperforating in a much more permeable interval, the flow rate varied from almost 1,600 kg/min (3,500 lb/min) at 1.7 bars (25 psig) wellhead gauge pressure to about 300 kg/min (660 lb/min) at about 6.4 bars (93 psig) pressure and 166°C (331°F). In Mesa 6-2 the rate varied from 1,100 kg/min (2,500 lb/min) at 2.1 bars (31 psig) and 134°C (273°F) with 7% steam by weight, to approximately 190 kg/min (420 lb/min) at 5.9 bars (86 psig) and 154°C (309°F) where the fluid is 100% liquid. In Mesa 5-1 the flow rate was measured at over 800 kg/min (1,800 lb/min) at 0.8 bar (12 psig) and 104°C (219°F). The fluid contained 6.2% steam, by weight, at the wellhead. The flow rate for Mesa 8-1 varied from 1,394 kg/min (3,073 lb/min) at 2.0 bars (29 psig) and 127°C (261°F) with 7.7% steam to about 190 kg/min (419 lb/min) at 6.8 bars (99 psig). Surface temperature and pressure of 120°C (248°F) and 1 bar (14.5 psi) were measured at Mesa 31-1, but no flow test results have yet been published.

Fig. 2.5 shows the variation of wellhead pressures and total flows with time for Mesa 6-2, 5-1 and 8-1 flowing full-open. Long-term full-open flow tests have not been conducted due to limited fluid disposal facilities and these tests have been terminated at 200 hours. Although the trends in Fig. 2.5 have little quantitative use because of the effect of scaling on the decreasing flow rates and pressures, it can be seen that equilibrium flow rates have not been achieved for any of the wells and that the decline in pressure and flow rate is similar for all three. Mesa 8-1 had the highest flow rates, from about 1,340 kg/min (2,950 lb/min) at approximately 2 bars (29 psig) to about 1,100 kg/min (2,400 lb/min) at approximately 1.6 bars (23 psig). Mesa 5-1 had the lowest flow rates, from about 880 kg/min (1,940 lb/min) at approximately 0.8 bars (12 psig) to about 500 kg/min (1,100 lb/min) at approximately 0.3 bars (4.4 psig). The full-open flow rate of Mesa 6-2 declined from about 1,140 kg/min (2,500 lb/min) at approximately 2.1 bars (31 psig) to about 800 kg/min (1,800 lb/min) at 1.7 bars (25 psig). During these tests some of the wells developed downhole calcium carbonate scales, especially Mesa 5-1, which was constricted to the point where it was impossible to lower small diameter instruments down the hole. Injection of 15% inhibited hydrochloric acid was necessary to clear the well bore. Further downhole pressure data is necessary to define fully the long-term flow characteristics (Mathias, 1975) of these wells.

Table 2.3 shows bottom-hole shut-in and flowing pressures and bottom-hole shut-in temperatures. The shut-in pressures and temperatures were measured after the wells had been idle for a few weeks. The flowing pressures were obtained at full-open conditions within a few hours of startup. The total flow rates are shown in Fig. 2.5.

TABLE 2.3

BOTTOM-HOLE SHUT-IN AND FLOWING PRESSURES AND TEMPERATURES EAST MESA WELLS (Mathias, 1975)

Mesa well number	Depth measured (m)	Bottom-hole shut-in pressure (bar gauge)	Bottom-hole pressure while flowing (bar gauge)	Total flow rate (kg/min)	Bottom-hole shut-in temp/depth (°C) (m)
6-1	2,422	219	159	1,600	204/2,442
6-2	1,809	169	134	1,134	188/1,816
5-1	1,814	169	156	800	157/1,830
8-1	1,821	168	157	1,394	179/1,830
31-1		No tests run			

Pressure drops between bottom-hole and wellhead of over 150 bars (2,176 psi) are shown for Mesa 6-1, 5-1 and 8-1, and drops of about 130 bars (1,886 psi) are shown for Mesa 6-2. Bottom-hole temperature of 204°C (400°F) was measured for Mesa 6-1 while wellhead temperatures ranged from 130°C (266°F) to 160°C (320°F). Similarly, temperature differences were observed from 188°C (370°F) bottom-hole to 134°C (273°F) to 154°C (310°F) wellhead for Mesa 6-2, from 157°C (315°F) bottom-hole to 104°C (219°F) wellhead for Mesa 5-1, and from 179°C (354°F) bottom-hole to 127°C (261°F) to 157°C (315°F) wellhead for Mesa 8-1.

Interference tests were conducted at Mesa 6-2 and Mesa 31-1 to determine transmissivity (Witherspoon, et al. 1976). Sensitive pressure gauges on wells Mesa 6-1 and Mesa 8-1 were used for observation measurements while Mesa 6-1 was flowing. Early drawdown data suggest a transmissivity of 11,200 millidarcy feet (md-ft) and a storage capacity (ϕcH) of 0.18 cm/bar (4.1 x 10^{-4} ft/psi). (The storage capacity is a measure of the volume of water yielded per square foot of aquifer per unit change in pressure). The data departs from the type curve after about 100 hours, possibly indicating a leaky boundary between 60 and 200 m (200 and 700 ft) from Mesa 6-1. The leaky boundary may represent the intersection of faults in the area (Fig. 2.3) or the deviation may be the result of observation well Mesa 6-2 tapping a different depth interval than Mesa 6-1.

An interference test was conducted on Mesa 31-1 with Republic Geothermal RG-38-30 used as an observation well. Type-curve matchings of the early drawdown data suggest a transmissivity of 29,500 md/ft (0.004 kg/sec) and a storage capacity of about 0.065 cm/bar (1.47 x 10^{-4} ft/psi).

The transmissivity here is almost three times that indicated from the tests at Mesa 6-1 while the storage capacity is somewhat more than one-third of that indicated for the Mesa 6-1 test. This test also indicates the presence of barrier boundary from 335 to 730 m (1,100 to 2,400 ft) from RG 38-30.

Flow rates and specific discharge during injection operations in Mesa 5-1 are shown in Fig. 2.6 (Mathias, 1975). The discharge curve starts to asymptotically approach about 45 cu m/day/m head (1 gpm/psi) after about 60 minutes of operation. Injection of fluid from a holding pond was started February 28, 1975 and continued sporadically at average flow rates from 300 to 1,281 cu m/day (55 to 235 gpm) (Table 2.4). As can be seen from Fig. 2.6 the specific injection rate decreased as the injected quantity of the 50,000 mg/l TDS, pH 7.5 fluid increased. Initially higher injection than discharge values are attributed to improved reservoir properties due to pre-perforation acidizing (Mathias, 1975). Pressure pumping began about 48 hours after injection started and after ten days it was up to 5.5 bars (gauge) (80 psi) at 398 cu m/day (73 gpm). Fluids were being less readily accepted and intermittent pumping was conducted, with a wide range of pressure and rate variations (Table 2.4). It was calculated that 1,030 kg (2,270 lb) of suspended solids were injected. The high corrosion noted in the lower portion of the hole was attributed to high quantities of dissolved oxygen (Shannon, 1975).

Chemical Composition of Fluids--
The geothermal fluids at East Mesa have relatively low salinity, ranging from about 1,500 mg/l in Mesa 5-1 and 8-1 to somewhat over 25,000 mg/l in Mesa 6-1. The lower salinity waters generally appear to have relatively higher bicarbonate content than the higher salinity waters which generally have high concentration of only sodium and chloride. Table 2.9 shows major constituent and trace element analyses of East Mesa geothermal wells and one analysis of water from the Mesa 6-2 holding pond.

The change of salinity (TDS) with depth is shown on depth vs. salinity (sodium chloride equivalent ppm) for 10 geothermal wells in the East Mesa geothermal field (Fig. 2.7). These plots are based on interpretation of electrical resistivity and self-potential well logs. In general, they show two higher salinity layers at 600 to 1,200 m (2,000 to 4,000 ft) and 1,800 to 2,300 m (6,000 to 7,500 ft) with a lower salinity layer between. The plots show fluid salinity increasing to 3,000 to 5,000 ppm at

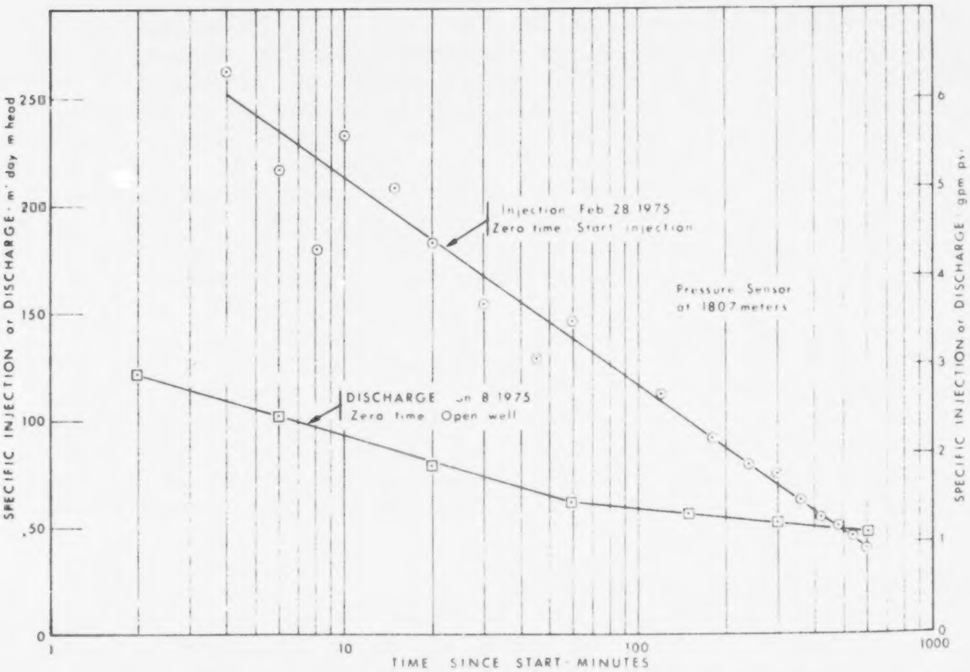


Figure 2.6 Specific injection and discharge at Mesa 5-1 during initial injection and discharge operations (Mathias, 1975)

TABLE 2.4 INJECTION SCHEDULE, MESA 5-1 (Mathias, 1975)

Date 1975	Time	Operation	Average flow rate (m^3/day)	Cumulative quantity flowed (m^3)
Feb. 28	1015	Begin injection	1 090	0
Mar. 11	0730	Stop injection	398	6 968
Mar. 11	1020	Begin injection	398	–
Mar. 12	0745	Stop injection	125	7 222
Mar. 12	0840	Begin injection with booster pump	1 281	–
	1330	Stop injection	600	7 416
	1450	Begin injection	441	–
	2100	Stop injection	578	7 490
Mar. 13	0915	Begin injection	1 128	–
		Average flow during injection	273	
Mar. 25	1525	Stop injection	343	11 184
Apr. 2	0955	Begin injecting shallow well water	300	–
Apr. 2	1300	Stop injection	300	11 441

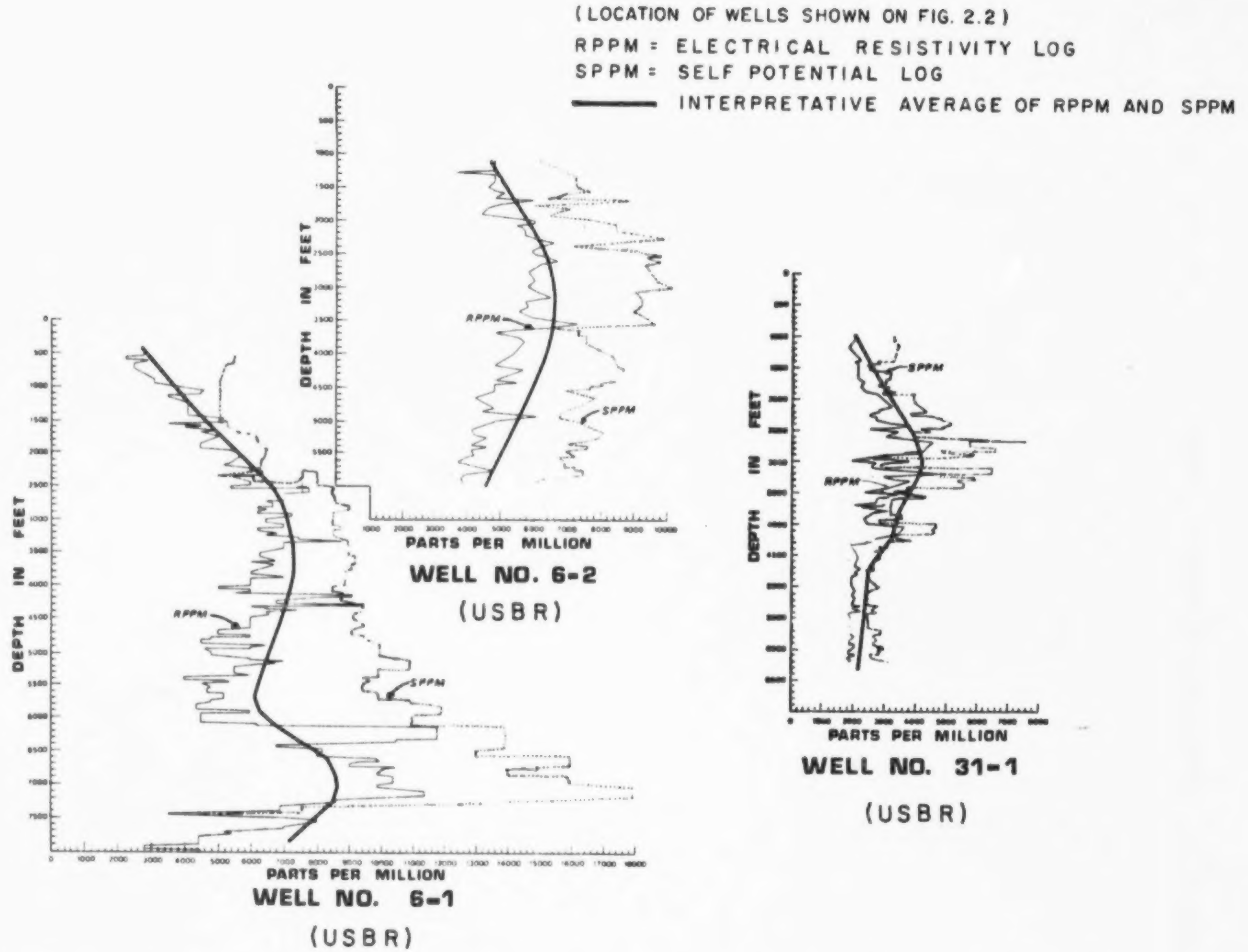


Figure 2.7 Chemical profile of geothermal wells, Mesa anomaly (Littleton and Burnett, in press) (continued)

(LOCATION OF WELLS SHOWN ON FIG. 2.2)
RPPM = ELECTRICAL RESISTIVITY LOG
SPPM = SELF POTENTIAL LOG
▬ INTERPRETATIVE AVERAGE OF RPPM AND SPPM

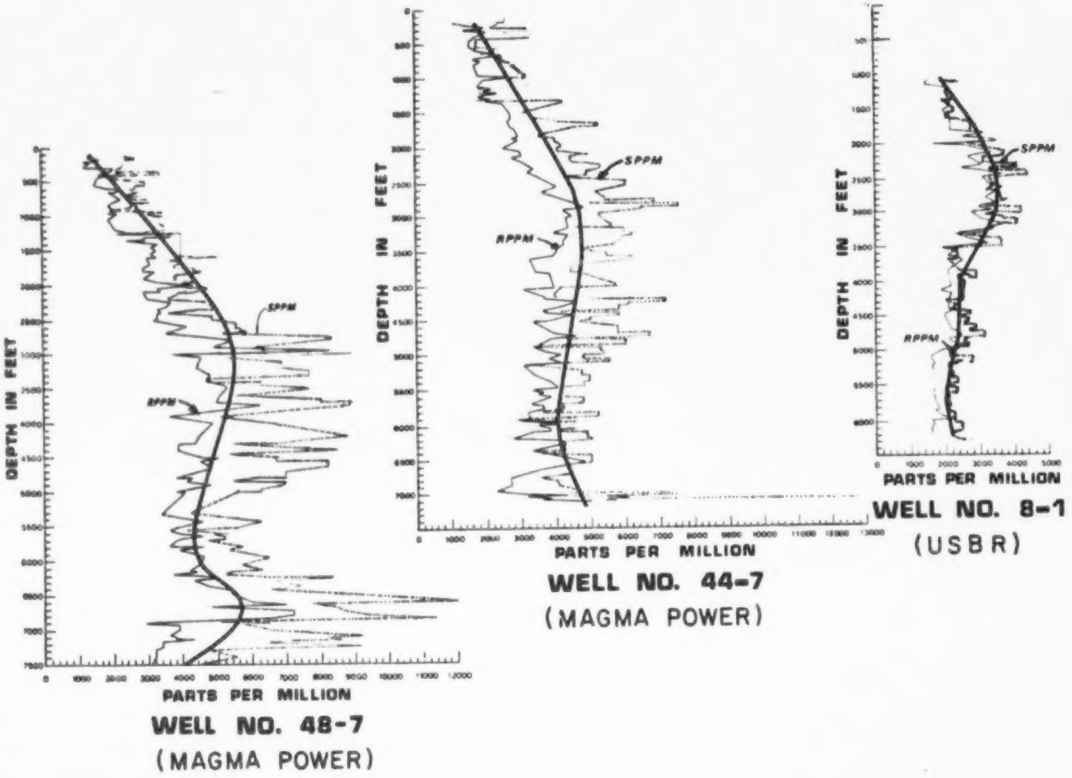


Figure 2.7 (continued)

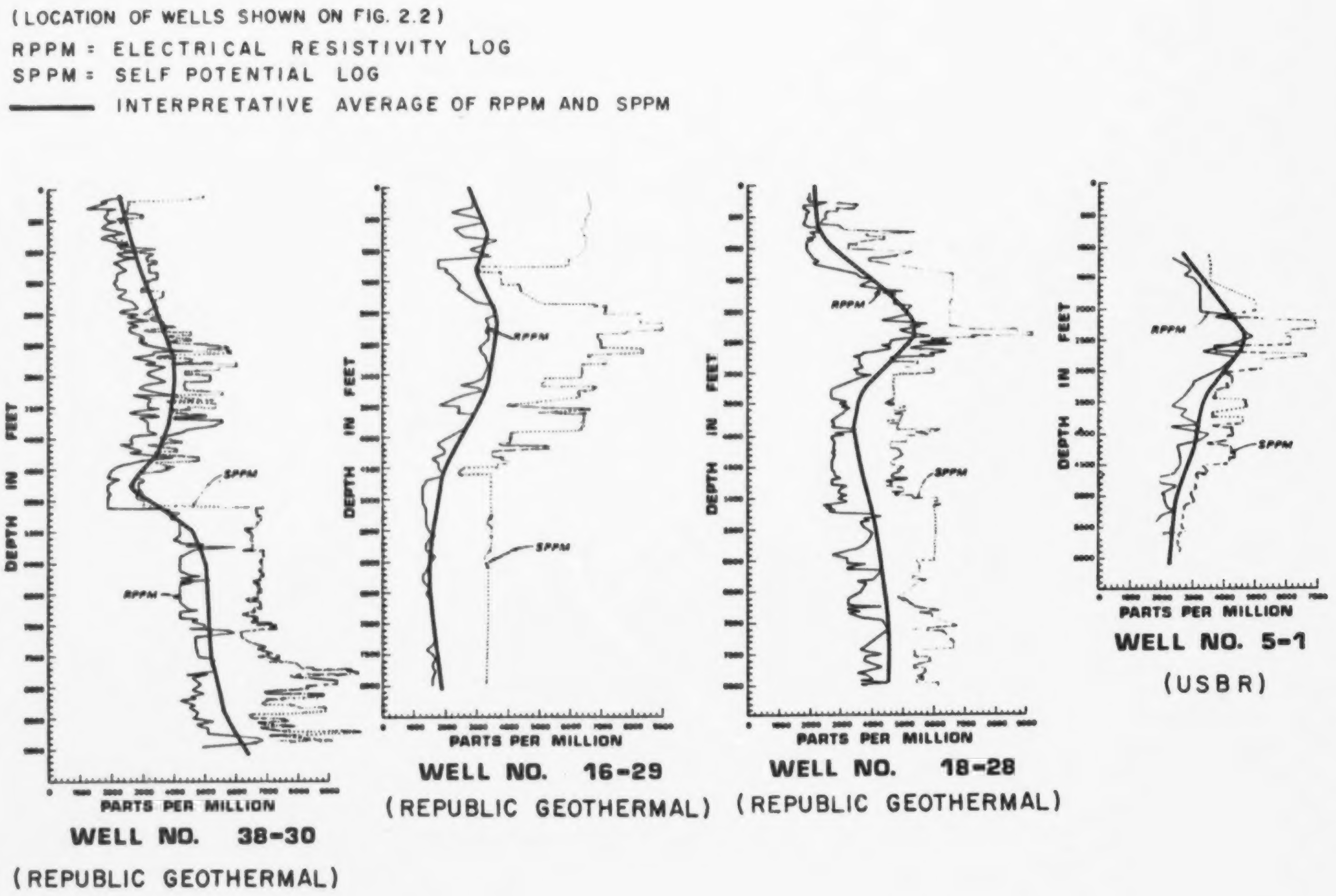

(LOCATION OF WELLS SHOWN ON FIG. 2.2)
RPPM = ELECTRICAL RESISTIVITY LOG
SPPM = SELF POTENTIAL LOG
INTERPRETATIVE AVERAGE OF RPPM AND SPPM
DEPTH IN FEET
PARTS PER MILLION
RPPM
SPPM
WELL NO. 38-30
(REPUBLIC GEOTHERMAL)
WELL NO. 16-29
(REPUBLIC GEOTHERMAL)
WELL NO. 18-28
(REPUBLIC GEOTHERMAL)
WELL NO. 5-1
(USBR)

Figure 2.7

750 to 900 m (2,500 to 3,000 ft) depth and then decreasing with depth to 2,000 to 4,000 ppm at 1,800 m (6,000 ft). Logs for wells 6-1 and 48-7 show a more concentrated brine of 5,000 to 9,000 ppm around the 2,100 m (7,000 ft) depth. The profile is different for wells 38-30 and 18-28, where the salinity starts increasing at about 1,460 and 1,160 m (4,800 and 3,800 ft) respectively and continues to increase for the total 2,400 to 2,700 m (8,000 to 9,000 ft) depth of the well log. The log for wells 6-1, 6-2, 18-28 and to some extent 48-7 in general show somewhat higher salinities than the remaining wells.

Relative to USPHS drinking water standards, the East Mesa fluids are high in arsenic, boron, cadmium, chloride, fluoride, iron, manganese, sulfate, and TDS. These potential pollutants are discussed in more detail in section 2.3.1 on water pollution in East Mesa.

Field Development Status--

USBR has been concentrating on evaluation of the East Mesa geothermal field since the early 1970s. Their participation has resulted in drilling and testing of the five geothermal wells previously discussed. They have initiated a pilot desalination program to determine the feasibility of desalting mineralized geothermal fluids (Fernelius, 1975). At the same time power generation feasibility studies and materials investigations will be conducted. Two desalination units have been installed and are successfully operating to produce 75 to 190 cu m (2,650 to 6,700 cu ft) of distilled water per day. No silica scaling has occurred and other scaling and corrosion problems have been minor.

In addition, USBR and ERDA (in conjunction with Lawrence Berkeley Laboratory) have designated East Mesa KGRA as a national geothermal test site to allow industry, institutions and private investigators to conduct tests of geothermal materials and equipment in actual field conditions. Magma Power Company is currently constructing an 11,200 net kW "dual binary cycle" plant. They expect it to be operational by the spring of 1978 (Hinrichs and Falk, 1977). This is viewed as a research plant and will require three production wells to provide approximately 290 kg (130 lb) of well flow per kW.hr, and two injection wells.

2.2.2 Salton Sea KGRA

The Salton Sea KGRA includes the southeastern part of the Salton Sea and adjacent land area (Fig. 2.2). This geothermal field contains the greatest quantity and highest temperature geothermal fluid of any area in the Imperial Valley. Unfortunately, exploitation of these great reserves is hampered by the technical problems caused by the extremely high salinity geothermal brines.

The Salton Sea geothermal anomaly is generally regular in shape and isothermal surface locations are apparently unaffected by geologic and structural features. Presently, the size and shape of the geothermal field appears to be controlled solely by distance from the magma body that caused the anomaly. It is hypothesized that the emplacement of the heat source is geologically very recent; hence, the heat decay necessary for the shape of the isothermal surfaces to define stratigraphic and structural features has not yet occurred (Randall, 1974). Recent volcanic activity is evidenced by the Salton Buttes, which are five rhyolite domes near the southeast shore of the Salton Sea. Emplacement of one of these domes has been dated at 16,000 to 50,000 years ago (Muffler and White, 1969).

The Salton Sea geothermal anomaly is an area of high heat flow and high temperature gradients. Hot brines, with temperatures to 360°C (680°F) at depths from 1,500 to 2,500 m (4,900 to 8,200 ft) have been recovered from the area. The fluids have salinities to 385,000 ppm with sodium, chloride and calcium as major constituents. These hot brines have produced a greenschist metamorphic facies below depths of 1,000 m (3,300 ft). A decarbonation reaction has been commercially exploited through the production of carbon dioxide from wells penetrating this facies (Randall, 1974).

The depth to bedrock, and hence thickness of the sedimentary section of interbedded fluviatile and lacustrine sands, silts and clays, varies from less than 3,300 m (10,000 ft) to more than 4,900 m (16,000 ft) (Rex, 1970). Superimposed on the pattern of thickening of sedimentary fill towards the center of the valley is the effect of many faults (see Geonomics, in press), producing vertical displacements in the thick sedimentary section. These displacements can be minor or up to about 700 m (2,300 ft), such as that shown on the Calipatria Fault in this area (Rex, 1970). These fault features, in addition to the discontinuous nature of the sediments, make stratigraphic correlations extremely difficult.

Resource Base and Production Potential--

The resource base of the Salton Sea geothermal field is estimated to contain about half of the total recoverable heat energy in the Salton Trough (Table 2.1). Renner, et al. (1975) estimate the total stored heat in the water and rock of the Salton Sea geothermal field as 8.7×10^{19} J (8.3×10^{16} BTU). Estimates of the recoverable resource range from 11×10^{18} J (1.0×10^{16} BTU) (Towse, 1975) to Biehler and Lee's (1977) range of 35.4 to 106.1×10^{18} J (3.4 to 10.1×10^{16} BTU). It is felt that Biehler's estimates are somewhat high and the actual amount of the recoverable resource is nearer to the lower estimate.

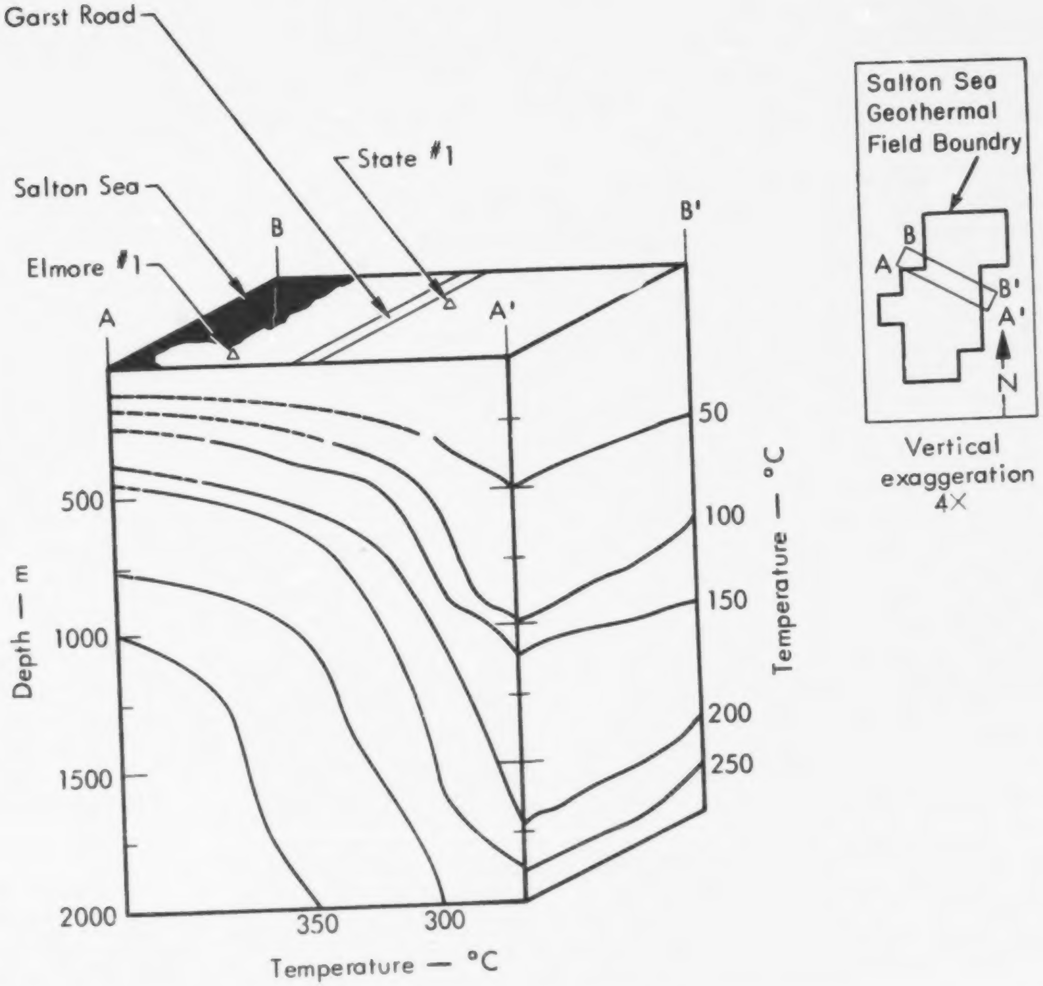
Status information is available for 24 geothermal wells drilled by private companies in the Salton Sea geothermal field

(Table 2.11) (Palmer, 1975). The first six wells were drilled in the late 1920s and early 1930s to depths between 180 m (590 ft) and 450 m (1,480 ft) and were used for carbon dioxide production. No additional drilling was done in the area until the late 1950s and early 1960s when 12 wells were drilled to depths between 520 m (1,700 ft) and 2,500 m (8,100 ft). Six more wells were drilled in the early 1970s to depths between 732 m (2,400 ft) and 1,331 m (4,368 ft). It appears from the narrower range of depths drilled in the 1970s that the producing geothermal intervals have become somewhat better defined with additional drilling and exploration.

Temperature gradient measurements are available for 17 individual geothermal wells and this information was compiled to construct a block diagram of isothermal surfaces for the Salton Sea geothermal field (Fig. 2.8) (Palmer, 1975). The diagram shows 50° to 350°C (122° to 662°F) isothermal surfaces for a northwest-southeast trending rectangular prism approximately in the middle of the KGRA. These data represent the best information available, but are not necessarily accurate due to differences in temperature measurement instruments, procedures and techniques. It is believed that some of the earlier data is for nonequilibrium conditions (Palmer, 1975). Fig. 2.8 shows individual isothermal surfaces closer to the ground surface under the Salton Sea, and located at greater depths to the east. From west to east the 50°C (122°F) isothermal surface occurs at depths from 100 m (330 ft) to 500 m (1,640 ft), the 100°C (212°F) surface occurs at depths from 150 m (490 ft) to 1,000 m (3,300 ft), the 250°C (482°F) surface occurs at depths from 450 m (1,480 ft) to 1,900 m (6,230 ft) and the 350°C (662°F) isothermal surface occurs at 1,000 m (3,300 ft) depth beneath the southeast shore of the Salton Sea. None of the isothermal surfaces vary linearly and the gradient increases steeply to the southeast. Common temperature ranges for wells in the Salton Sea KGRA are 200°C (390°F) to over 300°C (570°F).

Production data for geothermal wells in the Salton Sea KGRA are summarized in Table 2.5. These data, including wellhead pressure, orifice size and percent steam in the wellhead effluent, are mostly from California Division of Oil and Gas records and are considered reasonably reliable (Palmer, 1975).

Geothermal wells in the heated water reservoir of the Salton Sea KGRA will not flow naturally and must be stimulated to begin flowing. This is usually done by injecting nitrogen into the bottom of the borehole, thereby lifting the entire column of water. This allows for thermal expansion, reduction of fluid density, and initiation of flow, which generally continues unaided at relatively high production rates. Flow from these wells is typically several hundred thousand kilograms per hour, with 10 to 20% steam accompanying the hypersaline brine. The maximum listed flow rate at well IID No. 1 has been sus-



Garst Road
State #1
Salton Sea
B
B'
Elmore #1
A
A'
50
100
150
200
250
Temperature — °C
500
1000
1500
2000
Depth — m
350
300
Temperature — °C
Salton Sea Geothermal Field Boundry
B
A
B'
A'
N
Vertical exaggeration 4×

Figure 2.8 Block diagram of isothermal surfaces - Salton Sea geothermal field (Palmer, 1975)

TABLE 2.5 SUMMARY OF PRODUCTION CHARACTERISTICS FOR GEOTHERMAL WELLS IN SALTON SEA KGRA (Palmer, 1975)

Well	Production Rate (lb/hr)	Wellhead Pressure (psi)	Date	Steam (%)	Orifice (in.)
Magma max #1	542,000	160	4-28-72	13	8
Magma max #1	405,000	96	4-29-72	14	8
Magma max #1	349,000	102	4-30-72	14	8
Magma max #1	339,000	122	5-1-72	15	8
Magma max #1	369,000	117	5-2-72	10	8
Magma max #1	399,000	103	5-3-72	13	8
Magma max #1	467,000	110	5-4-72	14	8
Sinclair #3	593,000	185	5-23-63	12	8
Sinclair #4	450,000	250	5-2-64	20	-
IID #1	625,500	200	6-62 90-day Test	25	7
IID #1	172,000	585	12-8-65	10	-
IID #1	375,000	485	12-9-65	11	-
IID #1	462,500	385	8-2-65	14	-
IID #1	500,000	285	-	17	-
IID #1	532,000	185	-	20	-
IID #2	377,000	212	3-64	18	8
IID #2	440,000	225	3-64	18	8
IID #2	349,700	263	3-64	16	8
IID #2	319,700	215	3-64	15	8
IID #2	395,400	225	3-64	14	8
Sportsman #1	327,000	248	4-61	15	5-1/2
Sportsman #1	293,000	205	4-61	16	5-1/2
Sportsman #1	324,000	200	-	17	5-1/2
State #1	305,000	465	6-64	15	8
State #1	364,000	400	6-64	18	8
State #1	405,000	347	6-64	20	8
Elmore #1	316,000	-	-	35	-
Hudson #1	432,333	-	8-64 4-day Test	22	7
River Ranch #1	244,700	-	10-65	20	7

tained at 283,725 kg/hr (625,500 lb/hr) for a 90-day test period and the well Hudson No. 1 has sustained a 196,105 kg/hr (432,333 lb/hr) flow rate for four days. Several other wells have produced for up to 18 months without appreciable decrease in the flow rate (Helgeson, 1968). Wellhead pressures vary from 6.75 kg/sq cm (96 psi) to 41.1 kg/sq cm (585 psi) with orifice size varying from 14 cm (5.5 in.) to 20 cm (8 in.).

Chemical Composition of Fluids--

Chemical composition, including trace element analyses for Salton Sea KGRA geothermal wells, is tabulated in Table 2.12. The brine analyses show extremely high TDS contents, as high as 385,000 ppm. Sodium, chloride and calcium constitute essentially 100% of the major constituents, generally with chloride being the major anion, and the percent reactance of sodium usually being more than double that of calcium.

Concentrations of iron and manganese reach a few thousand mg/l, while concentrations of silica and strontium are in the hundreds to a thousand mg/l range, with one strontium analysis of 4,800 mg/l in Sinclair No. 4 well. Values of 1,200 mg/l nickel and 1,050 mg/l nitrate have been reported for Sinclair No. 4 and Pioneer No. 3 wells, respectively. The concentrations of aluminum, boron, barium, bromine, cadmium, lithium, ammonium, lead, rubidium and zinc commonly range from a hundred to several hundred mg/l in Salton Sea geothermal wells, with some anomalously high values of a few thousand mg/l for barium, rubidium and zinc in Sinclair No. 4 well. Arsenic, cesium, copper and fluorine typically occur in the few tens of mg/l range.

Field Development Status--

The lack of economic and practical methods for extraction of heat energy from the brines in the Salton Sea KGRA has prevented the development of this large, high temperature resource. The major problems are the high salinity of the brines, averaging 250,000 to 300,000 ppm TDS; corrosivity of the effluent; the significant amount (3% by weight) of noncondensible gases in the fluids; scale deposition; and high production rates (nominally 1.8×10^5 kg/hr [4×10^5 lb/hr]).

Numerous well production tests have been conducted since the early 1960s (Table 2.5), and power generation test facilities are presently being tested to evaluate scaling and corrosion control techniques. The first successful attempt at generating electric power using Salton Sea geothermal brines was a 3,000-kW steam-operated power plant constructed in 1965 at IID well No. 1. Minor amounts of electricity were produced but scaling and corrosion problems caused the plant to shut down.

In 1965, mineral recovery was accomplished by solar evaporation from brine ponds; calcium chloride, potassium chloride and other salts were marketed by Imperial Thermal products until declining mineral prices made the venture unprofitable.

Earth Energy Company also attempted to generate electric power and extract minerals from Salton Sea geothermal brines in 1964 and 1965. They operated out of River Ranch well No. 1 in the Niland area, but met with limited success.

The Colorado River Basin Regional Water Quality Control Board ruling in 1963, that prohibited geothermal well discharge to any channel draining into the Salton Sea, caused Earth Energy Company and Imperial Thermal Products to initiate reinjection of spent geothermal fluids in 1965. Brine from River Ranch No. 1 was injected into Hudson Ranch well No. 1 and brine from IID well No. 1 was injected into IID well No. 3.

Sinclair No. 4 well, located on the Sinclair Ranch, was used as early as 1966 in conjunction with 77 acres of evaporation ponds to produce calcium chloride. This operation is still continuing under the auspices of Lee Chemical. Sinclair wells began in 1972 to establish a reliable brine production and injection system, to address scaling and corrosion problems, and to study power production from geothermal brines. The operation is still underway; two Sinclair wells have been reconditioned, and well flow tests have been conducted to establish the nature of the fluids, determine well characteristics, identify hydraulic-mechanical relationships and set up dynamic system tests.

San Diego Gas and Electric Company (SDG&E), in conjunction with ERDA and LLL, has developed, is operating and is field testing a four-stage flash-binary simulated 10 MW electric power generation system. It is designed to accept flow from two production wells at 182,000 kg/hr (400,000 lb/hr) each, at 190°C (370°F) and 11.6 kg/sq cm (165 psig). As of April 1, 1977, the facility has accumulated over 2,580 hours of successful operation using the total flow from only one well (Magmamax No. 1) (Jacobson, 1977). The process has allowed 1) removal of scale, 2) anticipation of operational problems and 3) limitation of maintenance costs. Further modifications are planned to improve performance. Major problems have been with injection pump seals, scale deposition and injection well plugging.

New Albion Resources Company and Imperial Magma are currently operating two production wells and two injection wells to provide fluid supply and fluid disposal for the SDG&E/ERDA experimental facility at Niland. Magmamax No. 1 has been a prolific producer, with well head temperatures above 200°C (392°F) and volumes greater than 3,800 lpm (1,000 gpm). Woolsey No. 1 well had not initially produced enough fluid and was deepened to 1,064 m (3,490 ft). The flow rate has not yet been increased, but wellhead temperature and pressure have been greatly improved, to 93°C (200°F) and 28 kg/sq cm (400 psig), respectively. Magmamax No. 3 well accepts cool brine from the plant and Magmamax No. 2 well is connected as a backup well. Increasing wellhead injection pressures and buildup of scale in the injection pipeline after eight months of operation necessitated a workover of Magmamax No. 3. This resulted in the well accepting 1,500 lpm (400 gpm) at 14.8 kg/sq cm (210 psi) and 6,060 lpm (1,600 gpm) at 22.9 kg/sq km (325 psi) (Nugent and Vick, 1977). Union Oil Company had conducted a one year injection test at Niland during 1964 and 1965. The injection rate was 2,270 lpm (600 gpm) and there was no loss of injectivity or reservoir response during the entire test (Chasteen, 1975).

2.2.3 Heber KGRA

The Heber KGRA is located in the south-central part of the Imperial Valley (Fig. 2.2). Boreholes show that dominantly Quaternary deltaic sands and shales derived from Colorado River sources (Muffler and Doe, 1968) persist to a depth of at least 2,500 m (8,200 ft) (Randall, 1971), although a 25 m (82 ft) thick gabbroic sill was encountered in one well. The greatest basement depth thus far encountered in the valley is at Heber and is estimated from seismic surveys (Biehler, et al. 1964) to be 7 km (4.3 mi).

Based on deep and shallow borehole data, Rex, et al. (1972) estimate that the Heber heat flow anomaly occupies about 35 sq km (13.5 sq mi). Numerous geophysical surveys were conducted in the Heber area (Kovach, et al. 1962; Meidav and Furgerson, 1972), and it was found that the area has electrical resistivity and gravity anomalies associated with high heat flow. Meidav and Furgerson (1972) showed that the Heber field has a low resistivity anomaly, although it was noted that the observed resistivity contrast is small because the background resistivities are also very low (less than 2 ohm-m). These low background resistivities were probably caused by high water salinities resulting from incomplete mixing and sluggish transport of regional groundwater. The incomplete groundwater mixing was explained by Meidav and Furgerson (1972), who showed that the Imperial Fault in the Heber area serves as an aquitard which separates the brackish central valley waters from fresher waters to the east. Biehler (1971) discovered a 2 milligal (mgal) positive gravity anomaly over Heber of approximately the same shape and size as the region of high heat flow. This low gravity anomaly contrasts with the much larger positives found over the Salton Sea, Brawley and East Mesa geothermal fields. Biehler (1971) postulated that this lower gravity pointed to the possible existence of a pure steam phase at the Heber field, but to date, drilling has not confirmed his assertion. An analysis of a detailed gravity survey of the Heber area by the Chevron Oil Company indicates that the relative gravity high is surrounded by a moderate gravity low. This may indicate a selective leaching and deposition process whereby minerals are dissolved from the rocks on the periphery and deposited in the central portion of the field.

Chemical Composition of Fluids--

Major constituents of the geothermal fluids at Heber are sodium chloride, with notable calcium and sometimes bicarbonate. The TDS are generally between 10,000 and 17,000 mg/l, which is less than 10% of the TDS of the Salton Sea geothermal fluids. Analyses of Heber geothermal fluids are given in Table 2.15. Trace element analyses show up to 8 mg/l boron, up to 6.6 mg/l lithium, up to 168 ppm silica and up to 42 ppm strontium. The chemical constituents of the geothermal fluid are discussed in more detail in the water pollution section of this report.

Resource Base and Production Potential--

The resource base of the Heber geothermal reservoir, including the total stored heat contained in the rock and water, is estimated by Renner, et al. (1975) as 46.0 x 10^{18} J (43.6 x 10^{15} BTU) (Table 2.1). Estimates of the recoverable resource range from 3.5 x 10^{18} J (3.3 x 10^{15} BTU) (Towse, 1975) to Biehler and Lee's (1977) range of 8.3 to 25.0 x 10^{18} J (7.9 to 23.7 x 10^{15} BTU). The lower estimates are probably closer to the value of the actual recoverable resource.

The Heber area has been considered a potential heat anomaly since 1945 when the temperature log of the Amerada Timkin No. 1 oil test well showed a higher than average temperature gradient. Chevron drilled a shallow test hole in 1963 and confirmed the heat anomaly. Three additional wells were drilled in 1972. A program to determine production and injection capabilities of the Heber reservoir was initiated in 1973. Chevron's Nowlin Partnership No. 1 well and Magma's Holtz No. 1 well were produced and recovered fluids were injected into Magma's Holtz No. 1 well. Three more wells were drilled in 1974 for further tests. There are at present ten deep wells besides the Amerada Timkin No. 1 in the Heber field.

Direct heat-exchange operations may be feasible with Heber fluids so SDG&E is collecting information on heat exchanger performance from a recently installed test module at the Chevron Nowlin Partnership well No. 1. Presently information on production rates and reservoir estimates is proprietary. No power production facilities have been completed. A 50 MWe binary demonstration geothermal power plant is being considered for installation at the Heber site to be funded by ERDA, EPRI and several other organizations. A series of reports on this demonstration power plant project has been published by EPRI, (Geonomics [1976a] and Geonomics [1976b]).

2.2.4 Brawley KGRA

Detailed data on the Brawley KGRA are not presently available. A discussion from Geonomics (in press) is outlined below with additional reservoir and development data.

The Brawley KGRA, also known as the North Brawley geothermal area, is located southeast of the Salton Sea, near the town of Brawley (Fig. 2.2). Meidav (1972) identified the North Brawley thermal anomaly by the very low resistivity of 0.35-0.76 ohm-m at depths greater than 600 ft. This is a four-fold decrease in resistivity compared to surrounding rocks. An eight-fold increase in temperature gradient would be required to produce such a decrease in resistivity if salinity and stratigraphic factors are ignored. There is evidence of at least one and perhaps two hydrologic discontinuities from the Sand Hills to a few kilometers northwest of the town of Brawley which would signify faults and would account for salinity and/or stratigraphic changes along the line. These discontinuities are the Brawley and Calipatria Faults. The Brawley fault first appeared in the literature on maps by Rex (1970). Later, gravity surveys confirmed the presence of large vertical displacements beneath the valley alluvium.

The sedimentary section from 0-328 m (0-1,100 ft) in the Brawley area contains a lower percent volume of sand bodies than some other fields in the Imperial Valley. In Brawley, the Amerada Veysey No. 1 well has 61% sand. The deposits of usable and recoverable water in storage have been estimated to be about 3,900 m (13,000 ft) thick in Brawley (Dutcher, et al. 1972) and the depth to basement in this area is estimated to be about 6,100 m (20,000 ft) (Rex, 1970).

The Brawley anomaly exhibits no natural geothermal fluid discharge at the surface. Chemical analyses of geothermal fluids have not been published for the Brawley geothermal field but it is believed to have an average TDS content of 85,000 to 100,000 ppm. The reported fluid temperature of 200°C (390°F) is based on an old oil test (Renner, et al. 1975). Renner, et al. (1975) estimates the resource base, the total stored heat in the rock and fluid, as 12.6×10^{18} J (1.2×10^{16} BTU) (Table 2.1) where the size of the resource is based on a temperature gradient survey. Estimates of heat in the recoverable fluid range from 1.0×10^{18} (Towse, 1975) to 3.2×10^{18} J (9.5×10^{14} to 3×10^{15} BTU) (Nathenson and Muffler, 1975), with Biehler and Lee's (1977) "excess mass" estimate ranging from 13.2 to 39.6 $\times 10^{18}$ J (1.25 to 3.76 $\times 10^{16}$ BTU).

There has been interest in the private sector in developing this area and Union Oil Company presently plans to drill four exploratory wells (Palmer, et al. 1975).

2.2.5 Dunes and Glamis KGRAS

The Dunes and Glamis KGRAs are not yet considered to be viable geothermal resources in Imperial Valley. The present resource estimates are quite low, especially in comparison with the other thermal anomalies in Imperial Valley (Table 2.1).

They are on the order of 2 x 10^{18} J (1.9 x 10^{15} BTU) total resource base (Renner, et al. 1975), and less than 1 x 10^{18} J (0.9 x 10^{15} BTU) recoverable heat for each area (Towse, 1975). Therefore, only cursory coverage will be given to these areas and the following discussion, largely extracted from Geonomics (in press), outlines their setting, development and history.

Dunes Geothermal Area--

The Dunes geothermal area is located in southeastern Imperial Valley, east of Holtville and adjacent to the Sand Hills (Fig. 2.2). Numerous shallow wells have been drilled in the area and many have geophysical logs. Randall (1971) described upper portions of the Cenozoic section in terms of percent volume of sand bodies per 150 m (490 ft), and observed that major parts of the section contain as much as 90% unconsolidated, highly porous sand bodies, with minor amounts of shale. Elders and Bird (1974) noted the importance of these shale layers in confining the hydrothermal system, preventing surface expression. They observed that impermeable shale layers served as sites for silica deposition by the upward circulating hydrothermal waters. This continuing deposition eventually formed a mushroom-shaped cap rock that served to seal the hydrothermal system.

Coplen (1972) suggests that local waters are almost totally derived from the Colorado River. These waters are notably low in salts and therefore are vastly different from the waters in northern parts of the valley (Rex, et al. 1972).

Much of the known regional structure of the Dunes area has been deduced from geophysical studies. Kovach, et al. (1962) and Biehler, et al. (1964), on the basis of seismic refraction data, observed that basement depth increases from 700 m (2,300 ft) to 3,500 m (11,500 ft) as the Sand Hills are crossed from east to west. Numerous workers have postulated that a southeastern extension of the San Andreas Fault System traverses the axis of the Sand Hills (Biehler, et al. 1964; Garfunkel, 1972). Combs (1972) and Elders and Bird (1974) have speculated that this and related faults might be responsible in part for the formation of the Dunes hydrothermal system.

On the basis of shallow thermal gradient boreholes, the Dunes anomaly was discovered by Combs (1971). Combs (1972) suggested that the anomaly is an oval-shaped feature 2.5 sq km (1 sq mi) in area, with the hottest regions near the center; he also suggested the importance of the self-sealing mechanism. In the hottest holes, UCR No. 115 and DWR Dunes No. 1 (estimated heat flow 25 HFU; [Combs, 1972]), a silica-cemented sandstone was encountered between 60 and 115 m (197 and 377 ft) depth. Biehler (1971) completed a detailed gravity survey over the Dunes anomaly and obtained a 2-mgal positive closure that corresponds in shape with the thermal anomaly, although the gravity closure is centered almost 2 km (1.2 mi) to the northeast of the thermal anomaly. Biehler (1971) attributed this closure to the existence of the higher density silicified sand body as encountered at UCR No. 115. Black, et al. (1973) measured two orthogonal 3 km (1.9 mi) long resistivity profiles over the center of the Dunes anomaly, indicating that resistivity drops by 50% over the geothermal anomaly, at least to a depth of 200 m (660 ft). Van De Verg (1975, pers. comm.) did seismic refraction profiling over the Dunes and noted that basement depths do not change greatly at or near the Dunes anomaly. In summary, the Dunes anomaly can be characterized as a 2.5 sq km (1 sq mi) region of high heat flow, local positive gravity, and depressed electrical resistivity. However, the reversal of the temperature gradient at about 100°C (212°F) and 300 m (1,000 ft) depth (Coplen, et al. 1973) reduces hopes of developing this area at this time.

Glamis Geothermal Area--

The Glamis KGRA is about 32 km (20 mi) east of the town of Brawley, astride the Sand Hills and the trace of the San Andreas Fault (Fig. 2.2). Interest in this area was precipitated by a temperature gradient reported to be greater than 22°C/100 m (12°F/100 ft) (Rex, 1970). However, this gradient was based on one shallow drill and further exploration in this area has been disappointing. The initial drill hole probably intersected an isolated hot spring. Basement is shallow here and a gravity anomaly, often typical of geothermal reservoirs, is not present.

2.3 WATER POLLUTION POTENTIAL

Chemical characteristics of surface and ground water, as well as quantity and types of water use, are important inputs to evaluating potential environmental impact on the groundwater system. Study of waters allows comparison of relative chemical compositions, consideration of the relative merits of different water applications and comparison between the effects of current and projected water uses. To facilitate this comparison, tables have been compiled for Imperial Valley describing the wells, well use, water use, and well completion data (Tables 2.8, 2.11, 2.14 and 2.17). Separate tables giving chemical analyses for geothermal and nongeothermal waters in each KGRA have also been compiled from available data (Tables 2.9, 2.10, 2.12, 2.13, 2.15, 2.16, 2.18 and 2.19).

For this report, ground water in Imperial Valley was considered geothermal if it had a temperature 50°C (122°F) or higher. This rather high temperature was chosen based on groundwater use and the fact that summer ambient air temperatures reach this level. That is, some waters with temperatures from 20°C to 50°C (70°F to 122°F) were used for agricultural purposes or livestock watering, and these utilized waters must be considered in the baseline for comparison with potential effects of pollution by geothermally used production fluids. USPHS water standards (USPHS, 1962) were used in the discussions since they essentially represent the combination of the newly recommended National Interim Primary and Secondary Drinking Water Regulations [EPA, 1976, EPA, 1977a] Table 1.5).

It is important to note that detailed field work and further checks on well use and well properties would be necessary to accurately establish water use in each geothermal area. The data from the tables compiled for this report is probably incomplete or outdated. Many wells are listed with "other" uses or "unused." A well listed as an industrial well may, in fact, currently be a geothermal well; therefore, the water well survey should be updated and verified.

Comparisons of geothermal and nongeothermal uses and chemical characteristics, and comparisons of fluids with USPHS water standards, will be discussed below for each KGRA; an estimate of the amounts of pollutants released from the maximum potential power development will also be made. It is imperative to establish these baseline data and comparisons as early as possible. In fact, ranchers near the East Mesa geothermal area have charged that even pre-production geothermal test drilling has already had adverse effects on their water wells (Lofgren, 1974).

Potential hydrologic environmental impact of geothermal development in Imperial Valley can be divided into two categories: first, accidental escape of degrading geothermal effluents into the fresh groundwater system; second, accidental escape of degrading geothermal effluents onto agricultural land or into surface drainageways. The result of escaping geothermal fluid would be the increase, from natural conditions, in salinity and trace element concentration. This effect would vary depending on the degree of dilution involved in each potential mechanism and pathway, and on the concentrations of detrimental or toxic chemicals. It should be understood that chemical analyses for many trace elements and for many of the geothermal fluids are not available, and those that are available seem to be somewhat fortuitous in occurrence. Therefore, the discussion of trace elements is based on a very limited, and perhaps unrepresentative sample of analyses. However, they provide the most current and complete available data on the fluids in these areas. We must bear these limitations in mind and understand that as more data are gathered the picture may change.

Geothermal fluid escaping into the groundwater system in Imperial Valley may or may not degrade the naturally occurring groundwater depending on the composition of the geothermal fluid and the composition of the groundwater. The effects of the escape of geothermal fluid into the groundwater system would depend on the direction, rate and path of groundwater flow. A general idea of these properties is known for Imperial Valley, but there are also many individual zones where the direction and rate of motion departs from the general trend. This could occur at fault zones, buried stream channels, other permeable conduits or impermeable boundaries. This detailed structure is not presently known for any appreciable area in Imperial Valley, so discussion of the flow directions, rate and pollutant pathways must be limited to general trends and to potential pollution mechanisms and pathways, discussed in section 1.3.2. The potential pathways and mechanisms would be determined more specifically by detailed, site-specific geologic and hydrologic studies and specifications of detailed production and disposal methods at a particular site.

Despite the fact that the salinity of geothermal fluids is fairly high, the salinity of much of the naturally occurring groundwater is also high, so each area is discussed individually in the following sections. There are geothermal fluids in Imperial Valley with less than 2,000 mg/l TDS and there is naturally occurring groundwater with 10,000 to 15,000 mg/l TDS in the central part of the valley. Trace element content generally increases as salinity increases, so it would be expected that higher salinity fluids would also have higher trace element contents that may degrade natural ground or surface water.

Escape of geothermal fluid at the ground surface in a cultivated part of the valley would directly affect the current agricultural use of the land inundated and the salt balance of the irrigated tract. The degree of these effects would depend on the amount of escaping fluid. All other factors being equal, the greater the amount of fluid, the larger the area inundated. In the agricultural area the majority of the geothermal fluid would percolate down to the tile drain system and then be carried via canals and the New or Alamo Rivers into the Salton Sea. Quite a large amount of highly concentrated geothermal fluid would have to escape and drain into the Salton Sea to noticeably affect its salinity. Increase of Salton Sea salinity would only be a consideration if geothermal waters would be continually disposed of into the sea.

During the period 1961-1963, the average annual inflow to the Salton Sea from the Alamo and New Rivers and 30 other channels was 156,700 ha-m (1,300,000 acre-ft) or an average daily inflow of about 430 ha-m/day (3,500 acre-ft/day). Taking an extreme case and assuming an uncontrolled blowout of 75.8 kg/sec (167 lb/sec), a production well would produce 6,500,000 kg/day (14,400,000 lb/day) of geothermal fluid. Assuming the fluid has the density of seawater, 1,015 kg/cu m (63.86 lb/cu ft) gives a conservative estimate of 6,340 cu m/day (222,000 cu ft/day), or 0.63 ha-m/day (5.1 acre-ft/day) of escaping fluid. This amounts to somewhat more than 0.01% of the average daily inflow to the

Salton Sea. If the fluid had a concentration 200 times the average inflow concentration, this fluid would contain the amount of TDS equivalent to 20% of the average daily inflow. This type of inflow would have to continue uncontained for some period of time, probably more than a week or so, to have an appreciable long-term effect on the salinity of the Salton Sea, although, before adequate dilution, short-term effects may be significant in a localized area.

The effect of disturbing the salt balance of the inundated tract would be much more localized and much more pronounced. It would probably require re-flooding and percolating freshwater through the heavily salt-laden soil.

No organic pollutants are anticipated to be involved in disposal of geothermal effluents. Geothermal fluids are considered to be organically very clean due to the fact that the high temperatures and salinities provide an inhospitable environment for organisms. Geothermal development may produce some biological effects due to potential thermal, noise, air and water pollution. However, biological effects are beyond the scope of this report and will not be discussed.

Quantity of Produced Pollutants--

Estimates of the amount of chemical elements that would be produced by Imperial Valley geothermal fluids have been calculated in order to aid in assessing the potential environmental impact (Tables 2.6 and 2.7). These calculations for the East Mesa, Salton Sea, Heber and Brawley geothermal fields are based on the best available information on reservoir temperatures, resource potential and chemical constituents. However, these are currently only order of magnitude estimates, and will certainly change as further exploration, development and exploitation generates additional, more detailed data on the properties of the respective geothermal reservoirs. These limitations should be kept in mind when using the estimates.

The basis of the calculation is an estimation of the daily fluid production rate multiplied by the chemical constituent concentration. The production rate was estimated from a correlation chart of fluid temperature vs. MWe per 1,000 gpm flow rate (Geonomics, 1976b) and from the electric power output potential for each Imperial Valley geothermal reservoir. The reservoir temperature was taken from Renner, et al. (1975) and the corresponding MWe per 3,800 lpm (Mwe per 1,000 gpm) was read off the flash process curve of the Geonomics (1976b) correlation graph. The Nathenson and Muffler (1975) MWe - century estimate for electric power output potential for each reservoir was divided by 3.33 to arrive at a 30 year total production capacity estimate. Multiplying the potential production rate in MWe by the flow rate required per MWe for each reservoir gives the fluid production at maximum expected reservoir output. This number must then be converted from volume to mass to account for

TABLE 2.6 ESTIMATED DAILY FLUID PRODUCTION FOR IMPERIAL VALLEY GEOTHERMAL DEVELOPMENTS

KGRA	Average Temperature[1] (°C)	Maximum Estimated Electrical Capacity[2] (MW_e for 30 yr)	MW_e per 1,000 gpm[3]	Estimated Production Flow Rate (10^3 gpm	TDS (ppm)	Brine Density ρ_b[5] (lb/ft^3)	Total Brine Mass[6] (10^9 kg day)
East Mesa	180	490	1.4	350	2,000 to 30,000	53.7[7]	1.64
Salton Sea	340	2,800	10[4]	280	300,000	50.3	1.26
Heber	190	970	1.8	540	15,000	53.3	2.52
Brawley	200	330	2.3	140	100,000	55.9	.68
TOTAL		4,590		1,310			6.10

FOOTNOTES:

[1] From Renner, et al. (1975)

[2] From Nathenson and Muffler (1975) modified from $MW_e \cdot$cent to MW_e for 30 years

[3] From Geonomics (1976b), assuming flash process

[4] Subir Sanyal, personal communication, 1977

[5] $\rho_b = \rho_{stp}/B_w$ assuming one phase flow where ρ_{stp} is a function of TDS @ 14.7 psia and 60°F, B_w is a function of temperature and pressure, but pressure term is negligible at most wellhead pressures; therefore it has been omitted.

[6] Total Brine Mass (kg/day) = $\rho_b (lb/ft^3)$ x Flow Rate(gpm) x 0.1337 ft^3/gal x 0.4536 kg/lb x 1,440 min/day

[7] Average value from 53.3 lb/ft^3 for 2,000 mg/l TDS and 54.1 lb/ft^3 for 30,000 mg/l TDS

TABLE 2.7 ESTIMATED PROJECTED TOTAL DAILY CHEMICAL CONSTITUENT PRODUCTION FROM POTENTIAL GEOTHERMAL DEVELOPMENT IN IMPERIAL VALLEY

KGRA	Estimated Brine Production[1] (10^9 kg/day)	TDS[2] (ppm)	Total Solids Produced (10^6 kg/day)	Solids Produced for Constituent Concentrations of:						
				0.01 ppm	0.1 ppm	1.0 ppm	10.0 ppm	100 ppm	1,000 ppm	10,000 ppm
				(10^3 kg/day)						
East Mesa	1.64	2,000 to 30,000	3.28 to 49.2	0.0164	0.164	1.64	16.4	164	1,640	16,400
Salton Sea	1.26	300,000	378	0.0126	0.126	1.26	12.6	126	1,260	12,600
Heber	2.52	15,000	37.8	0.0252	0.252	2.52	25.2	252	2,520	25,200
Brawley	0.68	100,000	68.0	0.0068	0.068	0.68	6.8	68	680	6,800
TOTAL	6.10		487 to 533							

FOOTNOTES:

[1] From Table 2.10

[2] Estimated average

the difference in the density of the fluid at elevated geothermal temperatures and under the standard conditions of the chemical analyses. This conversion then allows computation of the total brine mass produced in 10^6 kg/day (22 x 10^6 lb/day) for each geothermal field at anticipated maximum production capacity (Table 2.6). Multiplying the total brine mass by the TDS (in appropriate units) gives an estimate of the TDS produced each day at each geothermal field (Table 2.7). Solids to be produced daily at each geothermal field for chemical constituents in concentrations from 0.01 ppm to 10,000 ppm are also given in Table 2.7. The table was constructed in this generalized manner to allow estimation by the reader of the quantity of any constituent (perhaps from analyses that were not available to us).

The total brine mass that would be produced from full-scale electric power production in Imperial Valley would be 6.10 billion kg/day (13.42 billion lb/day). This fluid would contain approximately 487 to 533 million kg/day (1,071 to 1,173 million lb/day) of TDS. Total fluid production for the projected 30 year power production would be about 6.7 x 10^{13} kg (14.7 x 10^{13} lb) and TDS in this fluid would be approximately 5.3 to 5.8 x 10^{12} kg (1.17 to 1.28 x 10^{13} lb). Estimates for individual fields are discussed in the respective subsections on each field.

One can obtain a very rough estimate of the total volume of the solids that would result from the full-scale development of geothermal power in Imperial Valley if all of the solids were extracted, as would occur, for example, if spent fluids were evaporated in holding ponds. Assuming a total solid mass of 5.3 to 5.8 x 10^{12} kg (1.17 to 1.28 x 10^{13} lb), to be generated over a 30 year period as discussed before, and a solid density of 2.165 g/cm^3 (density of sodium chloride crystals), the maximum volume of solids to be generated is 2.4 to 2.6 x 10^9 cu m (85 to 92 x 10^9 cu ft).

Data Sources--

The water use and water quality data used in this report were taken from the following sources:

"Selected Data on Water Wells, Geothermal Wells, and Oil Tests in Imperial Valley, California"; by W. F. Hardt and J. J. French (1976); a compilation of groundwater quality data for 436 wells; this source is a compilation of analyses that have previously been unpublished or have appeared in many separate publications.

"Chemistry of Thermal Water in Selected Geothermal Areas of California"; by M. J. Reed (1975); a report that includes chemical analysis of groundwater from 48 wells, mostly from the artesian aquifer in eastern Imperial Valley.

"Lawrence Berkeley Laboratory Brine Data File"; by S. Cosner and J. Apps (1977); a compilation including 27 chemical analyses of geothermal well waters in Imperial Valley.

"Geotechnical Environmental Aspects of Geothermal Power Generation at Heber, Imperial Valley, California"; by Geonomics (1976a); includes analyses of a number of geothermal wells in the Heber and Cerro Prieto geothermal areas.

"Preliminary Findings of an Investigation of the Dunes Thermal Anomaly, Imperial Valley, California"; by T. B. Coplen, et al. (1973); includes analyses of DWR Dunes well No. 1.

A complete field canvass was conducted by the USGS, Water Resources Division, Yuma in the 1960s and the results are included in Hardt and French (1976); the data contained is expected to give a fair representation of well use in Imperial Valley. Unfortunately, very little trace element data were available for the nongeothermal wells so most of the comparisons must be limited to major constituents.

2.3.1 Summary of Baseline Water Characteristics

Baseline chemical characteristics of groundwater in three depth intervals in Imperial Valley are presented in "Baseline Geotechnical Data for Four Geothermal Areas in the United States" (Geonomics, in press). The report includes discussion of the groundwater regime in the context of aquifer depth zones, or hydrologic depth units, in an attempt to define ground water flow within proposed hydrologic units; thus all chemical data that did not specify sample depth intervals were omitted from the survey. In this report, however, since water pollution is defined relative to existing or natural chemical composition and use, all water chemistry data have been included for comparison. For all geothermal and nongeothermal wells within 1.6 km (1 mi) of each Imperial Valley KGRA, tables have been prepared which describe 1) well location, completion data, water and well use, water level and yield, and 2) chemical composition. These tables allow comparison of water chemistry between geothermal and nongeothermal wells and will aid in defining chemical differences, potential pollution and the current uses of nongeothermal wells in the areas that are likely to be affected by geothermal development. Geonomics (in press) should be referred to for a detailed description of groundwater characteristics and distribution, hydrologic regimen and surface water characteristics.

A wide variation exists in the chemical character of geothermal fluids, groundwater and surface water in each of the Imperial Valley geothermal areas. The TDS content ranges from over 1,000 mg/l in East Mesa and the Dunes KGRAs to more than 385,000 mg/l (Cosner and Apps, 1977) in the Salton Sea KGRA. The Dunes sample is characterized by an appreciable proportion of calcium, sodium, sulfate and bicarbonate, similar to Colorado River water, while the Salton Sea geothermal fluid is characterized by high sodium and chloride with significant calcium. Three additional characteristic types of groundwater both geothermal and nongeothermal, have been defined in Imperial Valley by Geonomics (in press). They are a sodium bicarbonate water, a sodium chloride water, and a sodium chloride with high sulfate and/or magnesium water. The TDS content of these waters varies, depending on areal location and depth, from a few hundred mg/l to over 50,000 mg/l. Surface water quality varies from the purest waters running off the Peninsular Range to the west, to imported Colorado River water, to agricultural return water, to Salton Sea brine. Peninsular Range runoff commonly contains only a few hundred mg/l TDS. The TDS of Colorado River irrigation inflow has varied from 637 to 912 mg/l in the 25 years from 1941 to 1965 (Irelan, 1971) and is currently about 900 mg/l. The salinity of agricultural return waters flowing into the Salton Sea varies according to the proportions of canal water and drainage water. The range of TDS for the Alamo and New Rivers, flowing into the Salton Sea, is commonly about 2,500 to 7,000 mg/l. In 1967, the average TDS for Salton Sea water was about 36,000 mg/l, which is slightly more saline than seawater.

Because of these wide aerial variations in water character and quality each of the geothermal fields is discussed individually in an attempt to characterize the geothermal fluids and groundwater for each locality. However, a major factor to remember is that even in an individual locality the TDS content and amount of individual constituents can vary considerably. This is often exemplified in different samples from the same geothermal well (for example, see two analyses of well No. 811 [Magmamax No. 1] in Table 2.13).

2.3.2 East Mesa KGRA

Well and water use, and well completion data for all wells identified in and within 1.6 km (1 mi) of the East Mesa KGRA are given in Table 2.8. The locations of these wells are shown in Fig. 2.9. Of the 73 wells identified in this area, 12 have been used for domestic applications, four for industrial purposes, 40 are not used and there are 17 other or unknown applications. The pattern of well use shown in Fig. 2.9, with different symbols for domestic/industrial and geothermal wells, shows essentially all the domestic/industrial wells on the western portion

TABLE 2.8 DESCRIPTION OF WELLS IN AND WITHIN 1.6 KM (1 MI) OF EAST MESA KGRA*
(modified from Hardt and French, 1976)

MAP NUMBER	STATE NUMBER	OWNER OR NAME	YEAR DRILLED	OWNERSHIP	WATER USE	WELL USE	DIAM. (IN)	DEEPEST DEPTH (FT)	DEPTH CASED (FT)	DEPTH WELL (FT)	ALTITUDE OF LSD (FT)	WATER LEVEL (FT)	DATE WELL MEASURED	YIELD OF WELL (GPM)	CHEMICAL ANALYSES
205	15S/16E-22F01	D. STARR		P	H	W	2	650			3	F	7-61	3	x
208	15S/16E-24G01	USGS	1961	F	U	O	1	142	113	115	45	29	61		x
209	15S/16E-25G01	USBR 201	1973	F	U	H	6	503			42	18	11-73		
210	15S/16E-27N01	C. MARTINEZ		P	H	W	2				-3	F	7-61		x
215	15S/16E-35Q01	MAG EN SHARP 1	1972	N		Z		6,070			15				
216	15S/16E-36E01	B. NUSSBAUM	1961	P	H	U	6	630	360	430	40	F	7-61		x
217	15S/17E-20N01	USBR 126	1971	F	J	H	1	562			49				
219	15S/17E-29N01	USBR 203	1973	F	U	H	6	463			50	31	10-73		
220	15S/17E-30G01	USBR 202	1973	F	U	H	6	503			40	26	11-73		
221	15S/17E-31D01	U.C.R. #124		F	Z	H		562			30				
223	15S/17E-31N01	USBR 204	1973	F	U	H	6	403			34	11	11-73		
224	15S/17E-32R01	USBR 210	1973	F	U	H	6	303			75	51	12-73		
225	15S/17E-33D01	U.C.R. #125	1971	F	Z	T	1	511			71				
226	15S/17E-34N01	USBR 211	1973	F	U	H	6	323			80	51	12-73		
311	16S/16E-01B01	USBR 225	1974	F	U	H	4	1,105	1,100			F	3-74		
312	16S/16E-01C01	USGS-USBR	1975	F	Z	O	4	1,100							
313	16S/16E-01M01	I.I.D.	1947	W	Z		16	132	8	132	22	4	9-61		x
314	16S/16E-03C01	DATE CITY STORE		N	H	W		596			5	F	7-61		x
317	16S/16E-11K01	ALLENGRANZA-CLK	1972	P	H	W		1,166	1,008	1,166	17	F	4-72		
318	16S/16E-12A01	USBR 206	1973	F	U	H	6	503			20	2	9-73		
319	16S/16E-12N01	SCHNEIDER		P		W		825			20				x
320	16S/16E-12Q01	USGS	1961	F	U	O	1	142	103	105	30	13	10-61		x
321	16S/16E-12R01	USBR 223	1973	F	U	H	6	983			30	9	12-73		
322	16S/16E-13B01	LINDEN GRAVEL		N	N	W		810			30	9	12-73		x
323	16S/16E-14A01	KEITHMETZ #1	1950	N	H	W	2	800			17	F	9-61		x
325	16S/16E-15B02	OLD ALAMO STORE		P	H	W		1,117			12				
327	16S/16E-24A01	USBR 222	1974	F	U	H	1	343	343		35				
333	16S/17E-05D01	USPR 122	1971	F	U	H		562			65				
334	16S/17E-05D02	USGS-USBR	1975	F	Z	O	4	742	742		52				
335	16S/17E-05E01	USBR 123	1971	F	U	H		562			48				
336	16S/17E-06B01	USBR 205	1973	F	U	H	1	303	303		42				
337	16S/17E-06J01	USBR		F	Z	T		150			36				x
342	16S/17E-08F01	USBR 212	1973	F	U	H	6	313			47	29	10-73		
343	16S/17E-09K01	USBR 128	1971	F	U	H	2	562			57				

*see Appendix II for explanation

(continued)

TABLE 2.8* (continued)

MAP NUMBER	STATE NUMBER	OWNER OR NAME	YEAR DRILLED	OWNER SHIP	WATER USE	WELL USE	DIAM. (IN)	DEEPEST DEPTH (FT)	DEPTH CASED (FT)	DEPTH WELL (FT)	ALTITUDE OF LSD (FT)	WATER LEVEL (FT)	DATE WELL MEASURED	YIELD OF WELL (GPM)	CHEMICALS ANALYSES
344	16S/17E-12R01	USBR 214	1974	F	U	H	6	330			105	33	2-74		
345	16S/17E-14D01	USBR 213	1974	F	U	H	6	410			93	42	2-74		
346	16S/17E-16Q01	H. SCHAFER	1960	P	N	U	6	217	45	75	83	48	4-60		
347	16S/17E-16Q02	H. SCHAFER BARB 1	1958	N	N	P	10	8,017			84				
348	16S/17E-17B01	USBR 127	1971	F	Z	T	10	1,406			50				x
349	16S/17E-20N01	USBR 216	1974	F	U	H	1	432			45				
350	16S/17E-21A01	USBR 207	1973	F	U	H	6	498			85	42	10-73		
351	16S/17E-23R01	USGS	1964	F	U	O	1	177	155	157	90	34	2-64		x
352	16S/17E-27D01	USBR 217	1974	F	U	H	6	423			85	31	1-74		
356	16S/18E-15N01	USBR 221	1974	F	U	H	1	503			120				
357	16S/18E-17R01	USGS	1964	F	U	O	1	177	155	157	116	32	2-64		x
358	16S/18E-18R01	USBR 215	1974	F	U	H	6	330			112	31	2-74		
359	16S/18E-20R01	USBR 208	1974	F	U	H	1	510			120				
362	16S/18E-28L01	USBR 114	1971	F	Z	H	6	1,463			120	31	1-71		
363	16S/18E-28R01	USBR 218	1974	F	U	H	1	311			122				
364	16S/18E-29J01	USGS	1961	F	U	O	1	192	155	157	120	34	12-61		x
365	16S/18E-32G01	USBR 209	1974	F	U	H	1	525			117				
366	16S/18E-32R01	USGS LCRP 18	1964	F	U	O	10	815	140	630	118	28	6-64		x
416	17S/18E-01B01	IID		W	U	O					126				x
417	17S/18E-02B01	IID		W	U	O					124				x
418	17S/18E-03B01	IID		W	U	O					119				x
419	17S/18E-03B02	USBR 219	1974	F	U	H	1	528			119				
420	17S/18E-04A01	IID	1952	W	N	W	12	195	179	195	117				x
421	17S/18E-04B01	IID		W	U	O					115				x
422	17S/18E-05B01	IID		W	U	O					105				x
423	17S/18E-05R01	USBR 220	1974	F	U	H	1	332			105				
424	17S/18E-06A01	IID		W	U	O					101				x
425	17S/18E-06B01	IID		W	U	O					94				x
739	15S/16E-15P01	R. GAREWAL	1953	P	H	W	3	800			0	F	7-61		x
741	15S/16E-22L01	D. STARR	1943	P	H	W	2	750			2	F	7-61	3	x
742	15S/16E-23F01	L. FOSTER	1960	P	H	W	2	561	452	542	15	F	9-61	26	x
746	16S/16E-14A02	WATTON LABOR CAMP		P					1,128	1,128	17				x
747	16S/16E-15B01	ALAMO SCHOOL	1955	N	H	W	4	1,100	864	877	12	F	7-61	4	x
801	16S/17E-05A01	USBR MESA 5-1	1974	F	G	H		6,016			70				x
802	16S/17E-06J02	USBR MESA 6-1	1972	F	G	H	9	8,030	7,280	8,015	36	F	12-72		x

*see Appendix II for explanation

(continued)

TABLE 2.8* (continued)

MAP NUMBER	STATE NUMBER	OWNER OR NAME	YEAR DRILLED	OWNERSHIP	WATER USE	WELL USE	DIAM. (IN)	DEEPEST DEPTH (FT)	DEPTH CASED (FT)	DEPTH WELL (FT)	ALTITUDE OF LSD (FT)	WATER LEVEL (FT)	DATE WELL MEASURED	YIELD OF WELL (GPM)	CHEMICAL ANALYSES
803	16S/17E-06L01	USBR MESA 6-2	1973	F	G	H	11	6,005			24				x
804	16S/17E-08D01	USBR MESA 8-1	1974	F	G	H		6,205			50				x
805	15S/17E-31D02	USBR MESA 31-1	1974	F	G	H	8	6,231			30				x
910	15S/17E-30P01	REPUBLIC 38-30		N	G	H	7	8,890	6,383	7,022					
911	15S/17E-29N02	REPUBLIC 16-29		N	G	H		8,021							
912	15S/17E-28N01	REPUBLIC 18-28		N	G	H		8,001							
913	16S/17E-07L01	MAGMA 44-7		N	G	H		7,328							
914	16S/17E-07P01	MAGMA 48-7		N	G	H		7,528							

*see Appendix II for explanation

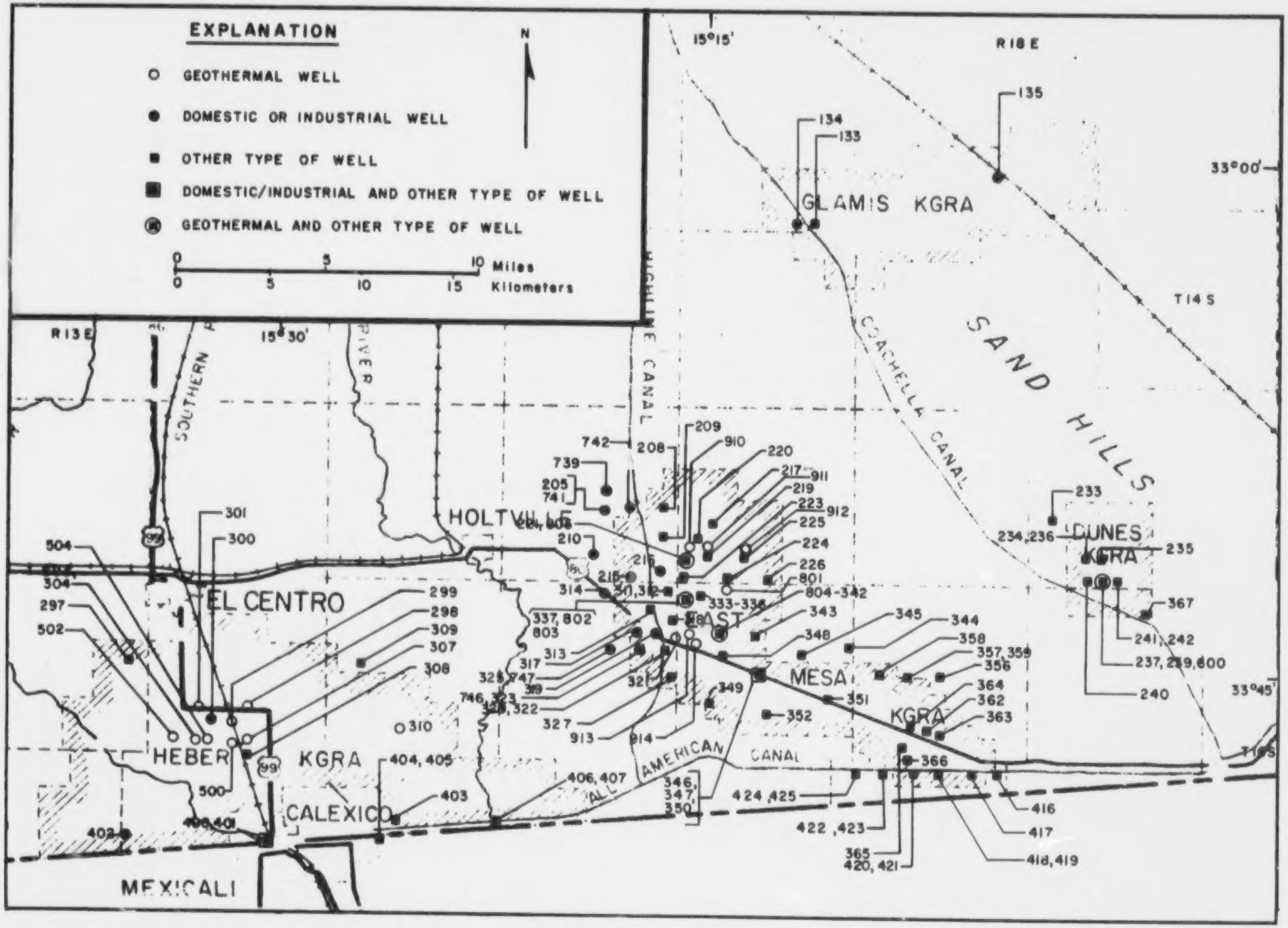

EXPLANATION
○ GEOTHERMAL WELL
● DOMESTIC OR INDUSTRIAL WELL
▪ OTHER TYPE OF WELL
■ DOMESTIC/INDUSTRIAL AND OTHER TYPE OF WELL
◉ GEOTHERMAL AND OTHER TYPE OF WELL
N
0 5 10 Miles
0 5 10 15 Kilometers
15°15'
R18E
R13E
15°30'
33°00'
33°45'
T14S
T16S
GLAMIS KGRA
SAND HILLS
COACHELLA CANAL
DUNES KGRA
HIGHLINE CANAL
SOUTHERN P
RIVER
HOLTVILLE
EL CENTRO
EAST MESA KGRA
ALL AMERICAN CANAL
HEBER KGRA
CALEXICO
MEXICALI
99
80
135
134
133
233
234,236
235
367
241,242
237,239,600
240
742
208
209
910
220
739
205
741
217
911
219
223
912
225
224
226
801
804-342
343
348
345
344
358
357,359
356
364
362
363
352
351
349
366
416
417
418,419
424,425
422,423
365
420,421
346
347
350
406,407
404,405
403
402
400,401
500
301
300
504
304
297
502
299
298
309
307
308
310
210
216
215
314
311,312
333-336
337,802
803
313
317
328,747
319
746,323
324,322
327
913
914
321

Figure 2.9 Location of wells in East Mesa, Heber, Dunes and Glamis KGRAs

of the East Mesa KGRA, with one oil or gas well (No. 346) towards the south-central part of the area and all the geothermal or "heat reservoir" wells in the central or eastern portion. Some of the domestic wells penetrate the artesian aquifer, with perforated intervals between 138 m (452 ft) and 267 m (877 ft).

The other domestic wells are up to 355 m (1,166 ft) deep. Many of the wells listed as "heat reservoir" are less than 330 m (1,000 ft) deep and therefore penetrate depths similar to those of domestic wells. The distinct areal separation in location of the domestic and geothermal wells possibly suggests a distinct hydrologic separation, either cultural, stratigraphic or structural or some combination. In fact, the contact between the Quaternary lake deposits (consisting of lacustrine silt, sand and clay), and the Quaternary alluvium (consisting of alluvial and deltaic sand, gravel and silt) is coincident with the line separating the two well-use areas, except for one domestic well tapping the artesian aquifer slightly to the east of the contact. This also happens to coincide with the division between the agricultural and nonagricultural land, i.e. the East Highline Canal.

The direction of shallow groundwater flow is generally northwest, and the domestic wells lie down-gradient from the geothermal wells. Therefore, assuming there is no hydraulic barrier between these two well areas, if geothermal fluids were injected in groundwater aquifers up-gradient from the domestic wells the fluids could eventually flow to them.

All available chemical analyses for East Mesa geothermal fluids are given in Table 2.9, and for nongeothermal fluids in Table 2.10. The chemical characteristics of the nongeothermal wells vary widely throughout the KGRA, from sodium chloride water in the shallow western portion to sodium bicarbonate water in the intermediate western portion, to waters with greater proportions of bicarbonate and/or sulfate in the eastern part. All of the domestic wells that have analyses available have 1,300 to 1,830 mg/l TDS content. This is a somewhat high TDS content for domestic water and is far above the USPHS recommended limit of 500 mg/l TDS.

Shallow and intermediate depth nonthermal groundwaters, occurring between 24 and 457 m (80 and 1,500 ft) in the East Mesa area, have TDS contents ranging from about 700 to 2,500 mg/l, with much of it under 1,000 mg/l. Although the analyses for some of the geothermal wells in the area show TDS contents not much above these domestic wells, in the 2,000 mg/l range, the anticipated production wells (e.g., Mesa 6-1, No. 802 on Table 2.9) will have TDS contents of 20,000 to 30,000 mg/l as well as significant amounts of trace elements. This implies a potential pollution threat if the more highly concentrated

TABLE 2.9 CHEMICAL ANALYSES OF GEOTHERMAL FLUIDS IN AND WITHIN 1.6 KM (1 MI) OF EAST MESA KGRA

MAP NUMBER	348	801	801[b]	802[c]	802[d]	802[d]
Date	1/73	4/74	5/74	7/73	2/74	6/76
Reference[a]	H	H	C	C	C	C
Units	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Temp.-C	83.3	-	131	166	166	166
pH	7.5	6.7	9.12	7.7	6.66	5.45
Sp.Grav.	-	-	-	-	-	-
Sp.C.-μmho	5,940	-	-	50,800	30,664	40,000
TDS-sum	3,267	2,390	1,575	33,250	18,847	26,300
Ca	44	46	16.2	1,360	642	1,360
Mg	3.2	4	2.1	20.8	13.8	17.2
Na	1,195	798	593	9,845	5,774	8,100
K	27	48	29	1,173	898	1,050
HCO_3	329	717	331.5	45.7	223	202
SO_4	60	196	102	<20	<10	42.8
Cl	1,710	825	454	19,400	10,942	15,850
Ag	-	-	-	-	0.06	<0.013
Al	-	-	-	-	-	0.04
Ar	-	-	-	-	0.009	-
As	-	-	-	-	-	0.2600
B	4.1	-	-	-	-	9.75
Ba	-	-	-	42	18	14
Br	-	-	-	-	-	-
Cd	-	-	-	<0.01	<0.04	<0.01
Cs	-	-	-	12.4	26	-
Co	-	-	-	-	-	0.06
Cu	-	-	-	0.06	0.03	<0.1
F	1.1	-	-	1.6	1.23	0.99
Fe	-	-	-	0.25	3.4	8.8
Hg	-	-	-	-	<0.0005	<0.002
Li	-	-	-	30	37	40
Mo	-	-	-	-	-	<0.005
Mn	-	-	-	1.26	0.95	0.95
NH_4	-	-	-	83	41	40.75
Ni	-	-	-	-	0.1	0.1
NO_3	-	-	-	<0.5	<0.5	<0.02
Pb	-	-	-	0.2	0.17	<0.5
PO_4	-	-	-	<1	<1	0.01
Rb	-	-	-	6	7.2	-
SiO_2	58	130	201	341	300	320
Sr	-	-	-	56	58	-
Zn	-	-	-	<0.005	0.1	-
Zr	-	-	-	-	-	-
H_2S	-	-	-	-	-	-
CO_2	17	229	-	-	-	-
Others	-	-[e]	-[e]	-[f,g]	-[f,h]	-[f,i]

(continued)

TABLE 2.9 (continued)

MAP NUMBER	803[d]	803[d]	804[d]	804[d]	805[d]	805[d]
Date	3/76	9/73	9/74	6/76	6/76	11/74
Reference[a]	C	C	C	C	C	C
Units	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Temp.-C	-	-	143	-	-	127
pH	6.12	7.70	7.68	6.27	6.27	7.72
Sp.Grav.	-	-	-	-	-	-
Sp.C.-µmho	6,000	3,862	-	3,200	4,700	-
TDS-sum	5,000	2,377	2,463†	1,600	2,900	2,311†
Ca	16.4	13	41.1	8.5	8.9	96.6
Mg	0.24	0.012	1.6	<0.05	<0.05	1.1
Na	1,700	760	723	610	730	782
K	150	68.8	42	70	85	25
HCO_3	560	715	668	417	845	467
SO_4	156	202	225	173	183	172
Cl	2,124	710	556	500	510	490
Ag	<0.01	<0.004	-	<0.01	<0.01	-
Al	0.03	-	-	0.02	0.02	-
Ar	-	-	-	-	-	-
As	.22	.045	-	.053	.025	-
B	7.45	-	3.3	1.6	2.5	2.2
Ba	0.25	<0.1	-	0.15	0.15	-
Br	-	-	-	-	-	-
Cd	<0.01	<0.002	-	<0.01	<0.02	-
Cs	-	1.82	-	-	-	-
Co	<0.01	-	-	<0.01	<0.01	-
Cu	<0.1	0.89	-	<0.1	<0.1	-
F	1.23	3.2	-	1.6	1.42	-
Fe	<0.1	0.06	1.1	<0.1	<0.1	2.4
Hg	<0.002	0.00735	-	0.014	0.008	-
Li	4	4	2	1.1	0.6	1.8
Mo	<0.005	-	-	<0.005	<0.005	-
Mn	0.05	<0.01	-	<0.05	<0.05	-
NH_4	14.7	17	-	4.95	2.45	-
Ni	<0.1	<0.02	-	<0.1	<0.1	-
NO_3	0.1	<0.1	-	0.34	0.43	-
Pb	<0.5	<0.02	-	<0.5	<0.5	-
PO_4	<0.2	0.8	-	<0.1	<0.01	-
Rb	-	0.6	-	-	-	-
SiO_2	269	250	263	389	274	88
Sr	6.4	.17	1.6	2.1	1.4	2.3
Zn	<0.01	0.008	-	<0.01	<0.01	-
Zr	-	-	-	-	-	-
H_2S	-	-	-	-	-	-
CO_2	-	-	-	-	-	-
Others	-[j]	-[k]	-	-[l]	-[m]	-

†TDS Residue on evaporation at 103°C

(continued)

TABLE 2.9 (continued)

FOOTNOTES

[a] H = Hardt and French, 1976
C = Cosner and Apps, 1977

[b] Flowing steam and brine

[c] Brine after steam flashed

[d] Unflashed brine

[e,f] The following radioactivity measurements are from O'Connell and Kaufmann, 1976. Sampling data are not specified.

^{222}Rn= 1240 ± 31.93 pCi/kg
^{226}Ra= 0.25 ± 0.08 pCi/l
^{234}U=<0.10 pCi/l
^{238}U=<0.10 pCi/l
^{230}Th= 0.80 ± 0.24 pCi/l
^{232}Th=<0.14 pCi/l

^{222}Rn= 1287 ± 61.12 pCi/kg
^{226}Ra= 190 ± 2 pCi/l
^{234}U= 0.12 ± 0.03 pCi/l
^{230}Th= 2.54 ± 0.28 pCi/l
^{232}Th=<0.10 pCi/l

[g] Be=<0.004
Cr= 0.03
Sb=<1
Se=<0.001
Sn=<0.2

[h] Be= 0.007
Bi= 0.4
Cr=<0.02
Sb= 0.7
Se=<0.003
Sn= 0.2

[i] Au=<0.01
Be=<0.02
Bi= 3
Ce= 2.75
Cr=<0.01
Ge=<0.1
In=<0.1
Ir=<0.1
Nb= 0.4
Pd=<0.1
Pt=<0.1

[j] Au=<0.01
Be=<0.02
Bi=<0.005
Ce= 0.38
Cr=<0.02
Ge=<0.1
In=<0.1
Ir=<0.1
Nb= 0.4
Pd=<0.1
Pt=<0.1
S= 1.5
Sb= 0.9
Se=<0.1
Ta= 0.17
Ti=<0.1
V=<0.005
W=<0.1

[k] Be=<0.005
Bi=<0.1
Cr=<0.04
Nb=<10
Sb=<0.2
Se=<0.001
Sn=<0.2
Ta=<5

(continued)

TABLE 2.9 (continued)

FOOTNOTES

[l] Au= 0.024
Be=<0.02
Bi=<0.005
Ce= 0.14
Cr=<0.01
Ge=<0.1
In=<0.1
Ir=<0.1
Nb= 0.4
Pd=<0.1
Pt=<0.1
S= 1
Sb= 1.2
Se= 0.5
Ta= 0.12
Ti=<0.1
V=<0.005
W=<0.1

[m] Au= 0.08
Be= 0.15
Bi=<0.005
Ce= 0.2
Cr=<0.01
Ge=<0.1
In=<0.1
Ir=<0.1
Nb= 0.4
Pd=<0.1
Pt=<0.1
S= 0.3
Sb= 1.0
Se= 1.8
Ta= 0.1
Ti=<0.1
V=<0.005
W=<0.1

TABLE 2.10 CHEMICAL ANALYSES OF WATER FROM NONGEOTHERMAL WELLS IN AND WITHIN 1.6 KM (1 MI) OF EAST MESA KGRA

MAP NUMBER	205	205	206	206	207	208	210
Date	3/58	7/61	7/61	12/70	12/70	1/62	7/61
Reference[a]	H	H	H	H	H	H	H
Units	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Temp.-C	37.2	32.2	37.8	34.7	34.1	-	31.7
pH	7.7	8.2	8.2	8.3	8.3	8.1	8.4
Sp.Grav.	-	-	-	-	-	-	-
Sp.C.-μmho	-	1,180	2,740	2,740	1,610	12,700	1,110
TDS-sum	1,674	663	1,550	1,600	987	7,110	706
Ca	17	4.8	17	17	6.7	384	6
Mg	6	1.7	5	5.5	2	232	1
Na	545	251*	571*	570	370	2,010*	264*
K	4	-	-	3.7	2.1	-	-
HCO_3	320	336	404	410	560	293	444
SO_4	124	52	135	170	140	217	80
Cl	588	163	588	600	160	4,120	100
Ag	-	-	-	-	-	-	-
Al	-	-	-	-	-	-	-
Ar	-	-	-	-	-	-	-
As	-	-	-	-	-	-	-
B	-	-	-	2.9	3.5	-	-
Ba	-	-	-	-	-	-	-
Br	-	-	-	-	-	-	-
Cd	-	-	-	-	-	-	-
Cs	-	-	-	-	-	-	-
Co	-	-	-	-	-	-	-
Cu	-	-	-	-	-	-	-
F	2.4	1.7	-	-	3.4	-	-
Fe	0.06	-	-	0.14	0.04	-	-
Hg	-	-	-	-	-	-	-
Li	-	-	-	0.16	0.13	-	-
Mo	-	-	-	-	-	-	-
Mn	-	-	-	-	-	-	-
NH_4	-	-	-	0.72	0	-	-
Ni	-	-	-	-	-	-	-
NO_3	0.08	-	-	-	-	-	-
Pb	-	-	-	-	-	-	-
PO_4	-	-	-	-	-	-	-
Rb	-	-	-	-	-	-	-
SiO_2	-	21	29	22	23	5	31
Sr	-	-	-	0.44	0.009	-	-
Zn	-	-	-	-	-	-	
Zr	-	-	-	-	-	-	-
H_2S	-	-	-	-	-	-	-
CO_2	10	3.4	4.1	3.3	4.5	3.6	2.8
Others	-	-	-	-	-	-	-

[a] H = Hardt and French, 1976

*Na + K value

(continued)

TABLE 2.10 (continued)

MAP NUMBER	216	313	314	314	319	320	322
Date	7/61	6/50	12/52	9/63	1/72	1/62	1/72
Reference[a]	H	H	H	H	H	H	H
Units	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Temp.-C	38.3	-	32.2	-	42	28.3	49
pH	8.3	-	8.1	8.2	8.3	8.0	7.8
Sp.Grav.	-	-	-	-	-	-	-
Sp.C.-µmho	1,360	1,320	1,380	1,510	-	4,340	-
TDS-sum	787	811	-	885	-	2,550	-
Ca	8.2	81	-	14	7	101	24
Mg	1.6	35	-	1	-	55	-
Na	300*	153*	304*	327*	315	750*	840
K	-	-	-	-	1.6	-	5.2
HCO_3	450	189	482	456	-	265	-
SO_4	76	310	98	100	-	600	-
Cl	159	142	161	187	154	900	995
Ag	-	-	-	-	-	-	-
Al	-	-	-	-	-	-	-
Ar	-	-	-	-	-	-	-
As	-	-	-	-	-	-	-
B	-	-	1.01	-	-	-	-
Ba	-	-	-	-	-	-	-
Br	-	-	-	-	0.2	-	0.8
Cd	-	-	-	-	-	-	-
Cs	-	-	-	-	-	-	-
Co	-	-	-	-	-	-	-
Cu	-	-	-	-	-	-	-
F	3	-	1.5	3	-	-	-
Fe	-	-	-	-	-	-	-
Hg	-	-	-	-	-	-	-
Li	-	-	-	-	-	-	-
Mo	-	-	-	-	-	-	-
Mn	-	-	-	-	-	-	-
NH_4	-	-	-	-	-	-	-
Ni	-	-	-	-	-	-	-
NO_3	-	-	-	-	-	-	-
Pb	-	-	-	-	-	-	-
PO_4	-	-	-	-	-	-	-
Rb	-	-	-	-	-	-	-
SiO_2	14	-	-	25	-	13	-
Sr	-	-	-	-	-	-	-
Zn	-	-	-	-	-	-	-
Zr	-	-	-	-	-	-	-
H_2S	-	-	-	-	-	-	-
CO_2	3.6	-	6.1	4.6	-	4.2	-
Others	-	-	-	-	-	-	-

[a]H = Hardt and French, 1976
*Na + K value

(continued)

TABLE 2.10 (continued)

MAP NUMBER	323	337	351	357	364	366
Date	12/70	3/72	10/63	9/63	2/64	6/64
Reference[a]	H	H	H	H	H	H
Units	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Temp.-C	43	33	-	33.9	-	-
pH	8.1	8.4	4.3	2.6	8.1	8.0
Sp.Grav.	-	-	-	-	-	-
Sp.C.-μmho	2,800	-	4,450	3,260	1,370	1,460
TDS-sum	1,520	-	2,620	1,960	804	874
Ca	17	24	130	65	12	23
Mg	3.5	-	5.2	8.3	7.3	8.6
Na	560	405	736	589	271*	272
K	3.6	3.9	-	-	-	4
HCO_3	300	-	-	-	192	208
SO_4	120	-	4	200	165	235
Cl	630	-	1,380	898	224	200
Ag	-	-	-	-	-	-
Al	-	-	-	-	-	-
Ar	-	-	-	-	-	-
As	-	-	-	-	-	-
B	3.4	-	-	-	-	0.64
Ba	-	-	-	-	-	-
Br	-	-	-	-	-	-
Cd	-	-	-	-	-	-
Cs	-	-	-	-	-	-
Co	-	-	-	-	-	-
Cu	-	-	-	-	-	-
F	2.1	-	-	1.2	1.9	1.7
Fe	0.05	-	-	-	-	-
Hg	-	-	-	-	-	-
Li	0.25	-	-	-	-	-
Mo	-	-	-	-	-	-
Mn	-	-	-	-	-	-
NH_4	0.52	-	-	-	-	-
Ni	-	-	-	-	-	-
NO_3	-	-	-	-	-	0.5
Pb	-	-	-	-	-	-
PO_4	-	-	-	-	-	-
Rb	-	-	-	-	-	-
SiO_2	26	-	16	-	27	27
Sr	0.57	-	-	-	-	-
Zn	-	-	-	-	-	-
Zr	-	-	-	-	-	-
H_2S	-	-	-	-	-	-
CO_2	3.8	-	-	-	2.4	3.3
Others	-	-	-	-	-	-

[a]H = Hardt and French, 1976
*Na + K value

(continued)

TABLE 2.10 (continued)

MAP NUMBER Date Reference[a] Units	416 7/64 H mg/l	417 7/64 H mg/l	418 7/64 H mg/l	420 6/64 H mg/l	421 7/64 H mg/l	422 7/64 H mg/l	424 7/64 H mg/l
Temp.-C	23.9	25	26.1	-	25	23.3	24.4
pH	6.5	7.8	9.0	7.8	10.1	7.9	10.0
Sp.Grav.	-	-	-	-	-	-	-
Sp.C.-μmho	1,180	1,190	2,920	1,170	1,410	1,070	1,730
TDS-sum	708	714	1,750	704	846	642	1,040
Ca	79	52	3.8	23	2	15	1.4
Mg	24	23	1.6	8.1	-	5.5	0.1
Na	131	169	718	213*	300	194	354
K	-	-	-	-	-	-	-
HCO_3	46	133	1,380	162	540	63	401
SO_4	312	300	190	208	105	217	258
Cl	152	121	175	143	74	144	124
Ag	-	-	-	-	-	-	-
Al	-	-	-	-	-	-	-
Ar	-	-	-	-	-	-	-
As	-	-	-	-	-	-	-
B	-	-	-	-	-	-	-
Ba	-	-	-	-	-	-	-
Br	-	-	-	-	-	-	-
Cd	-	-	-	-	-	-	-
Cs	-	-	-	-	-	-	-
Co	-	-	-	-	-	-	-
Cu	-	-	-	-	-	-	-
F	0.7	0.7	0.6	1.5	0.3	0.6	0.6
Fe	-	-	-	-	-	-	-
Hg	-	-	-	-	-	-	-
Li	-	-	-	-	-	-	-
Mo	-	-	-	-	-	-	-
Mn	-	-	-	-	-	-	-
NH_4	-	-	-	-	-	-	-
Ni	-	-	-	-	-	-	-
NO_3	-	-	-	-	-	-	-
Pb	-	-	-	-	-	-	-
PO_4	-	-	-	-	-	-	-
Rb	-	-	-	-	-	-	-
SiO_2	2	1	1	26	-	-	-
Sr	-	-	-	-	-	-	-
Zn	-	-	-	-	-	-	-
Zr	-	-	-	-	-	-	-
H_2S	-	-	-	-	-	-	-
CO_2	23	3.4	2.2	4.1	0.1	1.3	0.1
Others	-	-	-	-	-	-	-

[a] H = Hardt and French, 1976
*Na + K value

(continued)

TABLE 2.10 (continued)

MAP NUMBER	425	739	741	742	746	747
Date	7/64	12/70	12/70	12/70	12/70	12/70
Reference[a]	H	R	R	R	R	R
Units	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Temp.-C	27.8	32	34.7	34.1	43	37.2
pH	11.2	8.39	8.15	8.38	8.09	8.33
Sp.Grav.	-	-	-	-	-	-
Sp.C.-µmho	3,460	1,920	2,880	1,750	3,290	2,210
TDS-sum	2,080	1,460	1,830	1,300	1,680	1,420
Ca	1.4	7.6	17	6.7	17	10
Mg	0.1	2.7	5.5	2	3.5	2.7
Na	699	420	570	370	560	420
K	-	2.2	3.7	2.1	3.6	2.4
HCO_3	1,400	600	430	580	310	510
SO_4	-	160	170	140	120	130
Cl	198	220	600	160	630	310
Ag	-	-	-	-	-	-
Al	-	-	-	-	-	-
Ar	-	-	-	-	-	-
As	-	-	-	-	-	-
B	-	2.7	2.9	3.5	3.4	2.2
Ba	-	-	-	-	-	-
Br	-	-	-	-	-	-
Cd	-	-	-	-	-	-
Cs	-	-	-	-	-	-
Co	-	-	-	-	-	-
Cu	-	-	-	-	-	-
F	-	3.9	2.2	3.4	2.1	2.3
Fe	-	0.10	0.14	0.04	0.05	0.05
Hg	-	-	-	-	-	-
Li	-	0.12	0.16	0.13	0.25	0.10
Mo	-	-	-	-	-	-
Mn	-	-	-	-	-	-
NH_4	-	-	-	-	-	-
Ni	-	-	-	-	-	-
NO_3	-	-	-	-	-	-
Pb	-	-	-	-	-	-
PO_4	-	-	-	-	-	-
Rb	-	-	-	-	-	-
SiO_2	1	25	22	23	26	25
Sr	-	0.10	0.44	0.09	0.57	0.41
Zn	-	-	-	-	-	-
Zr	-	-	-	-	-	-
H_2S	-	-	-	-	-	-
CO_2	0.0	-	-	-	-	-
Others	-	-	-	-	-	-

[a] H = Hardt and French, 1976
R = Reed, 1975

geothermal fluid escaped into the shallow or intermediate groundwater system or to the surface waters.

In addition to possible increased salinity problems if geothermal fluid escapes into the groundwater or surface water systems, some trace element contamination may also result. For East Mesa geothermal fluids, trace elements that have been analyzed (Table 2.9), and are above USPHS limits for drinking water use (Table 1.8), are arsenic, barium, fluoride, lead, selenium and silver. Trace elements which are above USPHS recommendations are iron and manganese. Arsenic concentrations of 0.26 mg/l and 0.22 mg/l have been reported for Mesa 6-1 and 6-2 respectively. These values are about four to five times the 0.05 mg/l limit for arsenic. A number of high barium concentrations have been reported, up to 42 mg/l in Mesa 6-1, which is over forty times the 1 mg/l USPHS limit. Fluoride concentrations slightly above the 2.2 mg/l USPHS limit have been reported for Mesa 6-1. However, similar fluoride concentrations slightly over this limit have also been reported for domestic artesian wells. A lead concentration of 0.2 mg/l has been reported for Mesa 6-1, which is about four times the USPHS limit of 0.05 mg/l. A 0.5 mg/l concentration of selenium has been reported for Mesa 8-1, compared to the 0.01 mg/l USPHS limit. A silver concentration slightly over the 0.05 mg/l USPHS limit has been reported for Mesa 6-1. Concentrations of iron and manganese have been reported that are above USPHS recommendations. Values of 8.8, 2.2, and 1.1 mg/l iron have been reported for Mesa 6-1, 31-1, and 8-1, respectively, compared to the USPHS 0.3 mg/l recommendation. A 1.26 mg/l manganese concentration, about five times the USPHS recommendation, has been reported for Mesa 6-1.

Water salinity is an ubiquitous problem in East Mesa with respect to irrigation and livestock water, although the upper limit of 5,000 mg/l TDS for livestock may allow some of the less concentrated geothermal fluids to be used for this purpose. Trace element concentrations exceeding irrigation standards are boron and copper. Boron concentrations commonly range from over 2 to 10 mg/l for many geothermal wells, and from 2 to 3.5 mg/l for many domestic artesian wells. Boron concentrations over about 3 mg/l are not good even for boron-tolerant crops (Table 1.13) and concentrations over 1 mg/l are not good for boron-sensitive crops. A copper concentration of 0.89 mg/l is reported in Mesa 6-2 while the crop threshold value, the value where a farmer should become concerned about the concentration, is 0.1 mg/l.

Based on a production fluids TDS concentration from 2,000 to 30,000 mg/l, the projected total amount of dissolved solids brought to the surface by potential geothermal production at East Mesa is estimated to be 3.28 to 49.2 million kg/day (7.2 to 108 million lbs/day) (Table 2.7), or from 35.9 to 539 billion kg (79.2 to 1,188 billion lbs) over the anticipated 30 years of power production. This will result from an estimated total brine mass production of about 1.64 billion kg/day (3.62 billion lbs/day) (Table 2.6). For chemical constituents with concentrations of 0.1 ppm or 100 ppm, the daily plant chemical throughput would be 164 and 164,000 kg/day (362 and 362,000 lbs/day, respectively (Table 2.7). It is anticipated, however, that the great majority of these chemical constituents would be injected back into the hydrologic unit they were removed from, thereby minimizing pollution or waste disposal problems.

2.3.3 Salton Sea KGRA

Of the 31 wells listed on Table 2.11, Description of Wells in and within 1.6 km (1 mi) of the Salton Sea KGRA, at least 12 are geothermal wells. The location of these wells is shown in Fig. 2.10. None of the groundwater is used domestically in this area, although wells supply water for industrial or recreational use. The remaining well water is unused or is listed as having "other" uses. Only four of the wells are listed as water withdrawal wells and three of these are geothermal.

From this preliminary survey of groundwater use in the Salton Sea KGRA it seems that the major groundwater use is for potential geothermal energy production and therefore possible ground water degradation is not as critical here. This is supported by the fact that groundwater flow towards the Salton Sea leaves only one recreationally used well somewhat downgradient from the geothermal wells. However, the possibility of chemically degraded and thermally polluted shallow groundwater seepage recharging the Salton Sea must also be considered. At this point, little information is available concerning this mechanism.

The areal distribution of the different types of wells (Fig. 2.10) suggests a clustering of geothermal wells with the other well types around the geothermal cluster. There appears to be a general northeast-southwest trend to the geothermal well locations. They occur near the southeast shore of the Salton Sea, with a suggestion of clustering along the Brawley and Calipatria Faults. All of the wells in this area penetrate surficial Quaternary lake sediments.

The two samples of shallow depth interval (24 to 91 m [80 to 300 ft] depth) nongeothermal groundwater (wells No. 36 and 73), within the Salton Sea KGRA proper, seem to be a mixture of the characteristic sodium chloride calcium Salton Sea geothermal water, and the sodium chloride with high sulfate or magnesium Salton Sea water, although the TDS concentrations are much lower than either: 1,600 mg/l for well No. 36 and 5,600 mg/l for well No. 73 (Table 2.12). Two groundwater analyses just outside the KGRA boundary (wells No. 67 and 79 in Geonomics [in press]) are characteristic sodium chloride with high sulfate or magnesium

TABLE 2.11 DESCRIPTION OF WELL SITES AND WATER SAMPLES IN AND WITHIN 1.6 KM (1 MI) OF SALTON SEA KGRA* (modified from Hardt and French, 1976)

MAP NUM-BER	STATE NUMBER	OWNER OR NAME	YEAR DRILLED	OWNERSHIP	WATER USE	WELL USE	DIAM. (IN)	DEEPEST DEPTH (FT)	DEPTH CASED (FT)	WELL DEPTH (FT)	ALTI-TUDE OF LSD (FT)	WATER LEVEL (FT)	DATE WELL MEA-SURED	YIELD OF WELL (GPM)	CHEMICAL ANALYSES
31	11S/13E-10L01	PIONEER #1	1927	N	N		5	727	452	727	-231				
32	11S/13E-10L02	PIONEER #2	1927	N	N			1,263			-231				
34	11S/13E-13D02	J. MASSION		P	R	W	2				-226	F		9	x
35	11S/13E-13K01	E.E.INC HUDSON 1	1964	N	G	U	6	6,141	5,855	6,122	-220				x
36	11S/13E-22H01	USGS	1962	F	U	O	1	152	145	147	-229	+2	5-62		x
41	11S/13E-23P01	IMP PROD CAL 1	1964	N	G	U	7	4,840	4,435	4,806	-225				x
44	11S/13E-28K01	SALTON SEA CHEM	1932	N		Z		1,054			-175				
45	11S/13E-33F01	USGS-USBR SS 1	1975	F	Z	O	6	500			-227	+4	4-75		
46	11S/13E-33L01	MPC MAGMAMAX 3	1972	N	G	R	9	4,000	2,618	3,076	-226				
47	11S/13E-33L02	MPC MAGMAMAX 4	1972	N	G	O	3	2,567	2,376	2,518	-226				
48	11S/13E-33M01	MAGMAMAX 2	1972	N	G	H	20	4,368	3,784	4,360	-227				
52	11S/14E-19E01	CH. STATION 1	1935		G	Z	6	590			-216				
69	12S/13E-04Q01	SINCLAIR 2	1961	N	G	H					-217	4	8-62		
71	12S/13E-10D01	KIC SINCLAIR 1	1958	N	G	U	3	4,720	3,370	3,445	-214				
73	12S/13E-15L01	USGS	1962	F	U	O	1	127	113	115	-202	10	2-62		x
74	12S/13E-19A01	GRACE 1	1963	N	N	H	16	1,200	1,000		-216				
75	12S/13E-24G01	SARDI OIL BIFF 1	1962	N	U	U	11	6,350			-196				
76	12S/13E-24K01	SARDI 1	1961	N	N	P		5,620			-196				
806	11S/13F-27M01	E E ELMORE 1	1964	N	G	U	8	7,117	4,745	7,087	-225				x
808	11S/13E-23F01	O'NEILL IID 1	1962	N	G	U	7	5,230	4,900	5,212	-229				x
809	11S/13E-22J01	IMP PROD IID 2	1963	N	G	U	7	5,826	3,490	5,303	-230				x
810	11S/13E-23C01	IMP PROD IID 3	1965	N	G	R	8	1,699			-230				x
811	11S/13E-33Q01	MPC MAGMAMAX 1	1972	N	G	W	8	2,805	1,797	2,264	-222				x
812	11S/13F-10L03	PIONEER #3	1927	N	N			1,473			-231				x
813	11S/13E-24D01	EE RIVER RANCH 1	1964	N	G	U	6	8,100	3,890	8,093	-225				x
814	12S/13E-10D02	WGC SINCLAIR 3	1963	N	G	U	8	6,922	3,788	6,868	-213				x
815	12S/13E-04Q02	WGI SINCLAIR 4	1964	N	G	W	9	5,306	4,254	5,047	-217				x
816	11S/13E-23G01	SPORTSMAN 1	1961	N	G	U	5	4,729	3,980	4,720	-228				x
818	11S/13E-33R01	MPC WOOLSEY 1	1972	N	G	W	8	2,400	1,866	2,375	-222				x
901	11S/13E-27N01	ELMORE #3	1974	N	G	U	16	2,510	2,007	2,505					
902	11S/13E-25L01	SALTON SEA CHEM	1933	N		U	9	960	450	500					
	10S/13E-27B01	MUD VOLCANO, ETNA		surface water sample											x
	12S/12E-29N01	POE ROAD SPRING		surface water sample											x
	11S/11E-21P01	SALTON SEA		surface water sample											x
	11S/13E-22H01	ALAMO RIVER		surface water sample											x

*see Appendix II for explanation

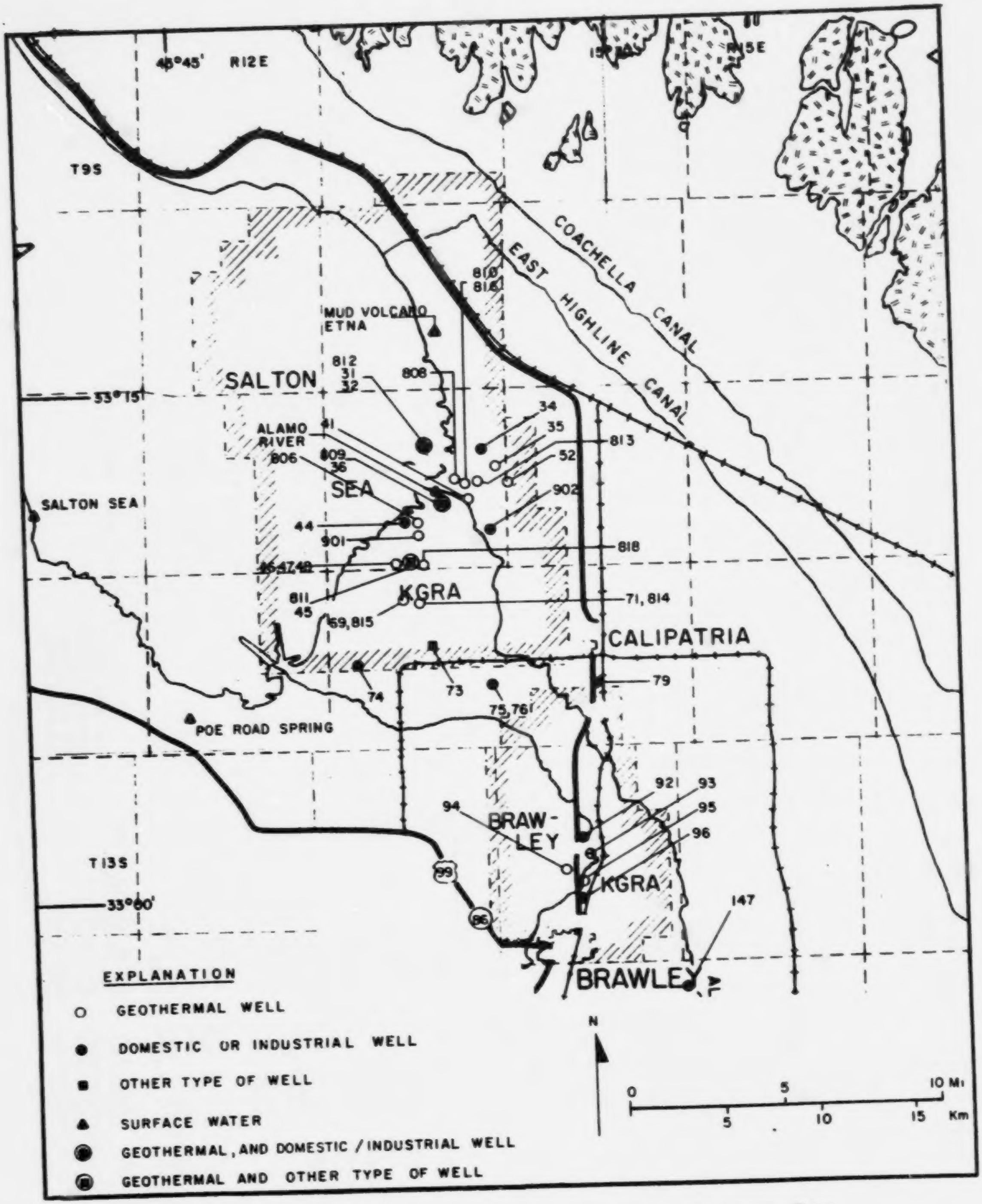

115°45' R12E
R15E
T9S
T13S
33°15'
33°00'
COACHELLA CANAL
EAST HIGHLINE CANAL
MUD VOLCANO ETNA
SALTON SEA KGRA
ALAMO RIVER
SALTON SEA
CALIPATRIA
POE ROAD SPRING
BRAWLEY KGRA
BRAWLEY
99
86
812 31 32
808
810 816
34
35
52
813
41
809 36
806
902
44
901
818
46 47 48
811 45
71, 814
69, 815
73
74
75, 76
79
92
93
94
95
96
147
EXPLANATION
○ GEOTHERMAL WELL
● DOMESTIC OR INDUSTRIAL WELL
■ OTHER TYPE OF WELL
▲ SURFACE WATER
GEOTHERMAL, AND DOMESTIC / INDUSTRIAL WELL
GEOTHERMAL AND OTHER TYPE OF WELL
N
0 5 10 Mi
5 10 15 Km

Figure 2.10 Location of wells in Salton Sea and Brawley KGRAs

TABLE 2.12 CHEMICAL ANALYSES OF WATER FROM SPECIFIED SITES AND NONGEOTHERMAL WELLS IN AND WITHIN 1.6 KM (1 MI) OF SALTON SEA KGRA

MAP NUMBER	36	73	Mud Volcano Etna	Mud Volcano Etna	Poe Road Spring	Poe Road Spring
Date	5/62	7/62	3/67	3/67	5/76	5/67
Reference[a]	H	H	CDWR	CDWR	CDWR	CDWR
Units	mg/l	mg/l	ppm	ppm	ppm	ppm
Temp.-C	27.8	27.8	20	-	21	-
pH	7.4	7.2	6.0	-	6.8	-
Sp.Grav.	-	-	-	-	-	-
Sp.C.-μmho	3,120	9,370	61,730	-	6,831	-
TDS-sum	1,600	5,600	51,632	-	4,656	-
Ca	134	476	2,083	-	249	-
Mg	49	202	1,714	-	285	-
Na	384*	1,300*	13,500	-	990	-
K	-	-	410	-	32	-
HCO_3	100	40	2,013	-	2,300	-
SO_4	275	700	1,536	-	453	-
Cl	710	2,900	27,900	-	1,150	-
Ag	-	-	-	<0.004	-	0.0001
Al	-	-	-	<0.15	-	0.2
Ar	-	-	-	-	-	-
As	-	-	-	-	-	-
B	-	-	84	-	5	-
Ba	-	-	-	<0.2	-	0.04
Br	-	-	-	-	-	-
Cd	-	-	-	<0.4	-	<0.005
Cs	-	-	-	-	-	-
Co	-	-	-	0.046	-	<0.0005
Cu	-	-	-	0.009	-	0.0054
F	-	-	3.6	-	0.6	-
Fe	-	-	-	0.10	-	0.080
Hg	-	-	-	<0.4	-	<0.2
Li	-	-	-	60	-	2.5
Mo	-	-	-	0.001	-	<0.002
Mn	-	-	-	3	-	0.240
NH_4	-	-	-	-	-	-
Ni	-	-	-	0.066	-	0.004
NO_3	-	-	17	-	24	-
Pb	-	-	-	0.0044	-	0.0024
PO_4	-	-	-	-	-	-
Rb	-	-	-	-	-	-
SiO_2	3	2	-	-	-	-
Sr	-	-	-	150	-	8.4
Zn	-	-	-	0.02	-	0.0080
Zr	-	-	-	-	-	-
H_2S	-	-	-	-	-	-
CO_2	6.4	4	-	-	-	-
Others	-	-	-	-[b]	-	-[c]

*Na + K value

(continued)

TABLE 2.12 (continued)

MAP NUMBER	Salton Sea	Salton Sea	Alamo River	Alamo River	34
Date	6/67	6/67	5/67	3/67	2/68
Reference[a]	CDWR	CDWR	CDWR	CDWR	H
Units	ppm	ppm	ppm	ppm	mg/l
Temp.-C	25	-	24	-	40
pH	7.7	-	8.0	-	-
Sp.Grav.	-	-	-	-	-
Sp.C.-μmho	42,100	-	3,510	-	33,780
TDS-sum	37,032	-	2 538	-	23,270
Ca	954	-	191	-	854
Mg	1,078	-	101	-	232
Na	10,500	-	483	-	7,200
K	172	-	14	-	504
HCO_3	203	-	220	-	1,684
SO_4	8,146	-	782	-	377
Cl	15,000	-	639	-	12,420
Ag	-	0.0008	-	<0.004	-
Al	-	<6	-	<0.1	-
Ar	-	-	-	-	-
As	-	-	-	-	0.03
B	9.2	-	0.26	-	50
Ba	-	<0.002	-	0.02	-
Br	-	-	-	-	2.5
Cd	-	<0.005	-	<0.4	-
Cs	-	-	-	-	-
Co	-	<0.0005	-	<0.002	-
Cu	-	0.005	-	0.0074	-
F	3.2	-	0.9	-	1.8
Fe	-	0.010	-	0.032	-
Hg	-	<0.2	-	<0.4	-
Li	-	-	-	0.133	-
Mo	-	0.016	-	0.0016	-
Mn	-	0.01	-	0.038	-
NH_4	-	-	-	-	-
Ni	-	0.003	-	0.0032	-
NO_3	14	-	31	-	0
Pb	-	<0.002	-	0.0034	-
PO_4	-	-	-	-	-
Rb	-	-	-	-	-
SiO_2	-	-	-	-	-
Sr	-	11	-	0.76	-
Zn	-	0.062	-	0.011	-
Zr	-	-	-	-	-
H_2S	-	-	-	-	-
CO_2	-	-	-	-	-
Others	-	-[d]	-	-[e]	I=3.9

(continued)

TABLE 2.12 (continued)

FOOTNOTES

[a] H = Hardt and French, 1976
CDWR = Cal. Div. Water Resources, 1970

[b] Au=<0.04
Be=<0.004
Bi=<0.08
Cr=<0.002
Ga=<0.08
Ge=<0.2
La=<0.08
Sb=<0.4
Sn=<0.08
Ti=<0.5
Tl=<0.08
V= 0.01

[c] Be=<0.002
Bi=<0.0005
Cr=<0.001
Ga=<0.0005
Ge=<0.1
Sb=<0.2
Sn=<0.04
Ti=<0.04
V=<0.002

[d] Au=<1
Be=<0.0005
Bi=<0.005
Cr=<0.002
Ga=<0.0005
Sb=<0.2
Sn=<0.04
Ti=<0.04
V= 0.003

[e] Au=<0.04
Be=<0.004
Bi=<0.08
Cr=<0.002
Ga=<0.08
Ge=<0.2
La=<0.08
Sb=<0.4
Sn=<0.08
Ti=<0.04
Tl=<0.08
V= 0.0066

waters with TDS concentrations of 1,490 and 15,200 mg/l, respectively. Although these waters are too saline for drinking or irrigation uses some of the lower salinity fluids may possibly be suited for livestock applications.

The rest of the wells in the area penetrate the deep depth interval (deeper than 457 m [1,500 ft]) and contain highly saline sodium chloride calcium brines with TDS contents from 34,000 to over 300,000 mg/l, with about 200,000 mg/l average (Table 2.13). This is obviously very saline water--not suitable for any drinking, irrigation or livestock use.

Highly concentrated brines such as the geothermal fluids also commonly have high trace element concentrations, which are discussed below (Table 2.13). However, it should be kept in mind that to isolate one component of the brine and call it toxic when the entire brine itself is toxic may be somewhat misleading.

Boron concentration, a critical element for agricultural applications, ranges from 92 mg/l in well No. 815 to 540.5 mg/l in well No. 816. This is far above the 0.33 to 0.67 mg/l range acceptable to boron sensitive crops (Table 1.13). There are no boron analyses available for nongeothermal wells in this area; however boron content for surface water ranges from 5 ppm at Poe Spring, to 9.2 ppm at the Salton Sea, to 94 ppm in the Etna mud volcano (Fig. 2.10). The boron content of agricultural return water measured at the Alamo River (Fig. 2.10) had values of 0.42, 0.8, 0.7 and 0.26 in 1955, 1960, 1964 and 1967, respectively. Even the highest value here is within the "permissible for sensitive crops" range (Table 1.13). Boron contamination would be an extremely serious problem in the agricultural economy of Imperial Valley.

The geothermal fluids are also above USPHS drinking water standards (Table 1.8) in cadmium, arsenic, fluoride, copper, barium, iron, lead, manganese, silver, zinc and radium-$_{226}$.

Cadmium concentrations, above the USPHS drinking water standard of 0.01 mg/l, of 2 ppm and less than 40 ppm are reported for wells No. 808 and 815, respectively, while surface water samples from the Etna mud volcano and Alamo River are less than 0.4 ppm.

Arsenic concentrations, above the USPHS drinking water standards limit of 0.05 mg/l, are reported to be 0.16 to 100 mg/l at wells No. 810 and 815, respectively. There are no arsenic analyses currently available for other wells or surface water.

Fluoride concentrations in geothermal wells range from an acceptable level of 0.8 mg/l in well No. 815 to 15 ppm in well

TABLE 2.13 CHEMICAL ANALYSES OF GEOTHERMAL FLUIDS IN AND WITHIN 1.6 KM (1 MI) OF SALTON SEA KGRA

MAP NUMBER	41[b,c]	806[d]	808[e]	808	809[c]	810[f]
Date	-	-	4/66	5/73	-	3/65
Reference[a]	C	C	C	C	C	H
Units	ppm	mg/l	ppm	mg/l	ppm	mg/l
Temp.-C	-	191.1	300	315.5	-	146
pH	-	4.9	5.2	-	4.64	7.5
Sp.Grav.	-	-	-	-	-	1.023
Sp.C.-μmho	-	-	-	-	-	47,600
TDS-sum	219,500	318,000	257,800	300,000†	259,000	35,963
Ca	21,100	31,500	28,000	33,000	27,800	1,130
Mg	27	16	54	37	10	74
Na	47,800	62,800	50,400	51,000	53,000	10,600
K	14,000	20,800	17,500	20,000	16,500	1,250
HCO_3	-	40	150	-	-	574
SO_4	-	49	5.4	-	-	621
Cl	12,700	185,000	155,000	182,300	155,000	19,700
Ag	<1	-	1.40	-	<1	-
Al	-	<15	4.20	22	-	2
Ar	-	-	-	-	-	-
As	-	-	-	7	-	0.16
B	290	350	390	410	390	100
Ba	190	480	235	230	250	3
Br	-	-	120	40	-	15
Cd	-	-	2	-	-	-
Cs	17	-	14	-	20	-
Co	-	-	T	-	-	-
Cu	2	12	-	26	3	-
F	-	-	15	-	-	1
Fe	1,200	2,500	2,290	2,600	2,000	0.7
Hg	-	-	0.006	-	-	-
Li	180	270	215	290	210	40
Mo	-	-	-	-	-	-
Mn	950	570	1,400	2,000	1,370	6.4
NH_4	-	-	409	-	-	321
Ni	-	-	-	0.48	-	-
NO_3	-	-	-	-	-	9.0
Pb	80	100	120	120	80	-
PO_4	-	-	-	-	-	-
Rb	65	-	135	-	70	-
SiO_2	-	-	400	1,500	400	120
Sr	-	1,050	400	470	440	85
Zn	500	-	540	600	500	-
Zr	-	-	-	-	-	-
H_2S	-	-	-	-	-	-
CO_2	5,000	-	-	-	500	29
Others	S=30	Cr=<1	Au=0 S=16 Sb=0.4 Sn=0.5 Tl=1.5	Be=<0.1 Cr= 0.16	S=30	I=4.5

†TDS Residue on evaporation

(continued)

TABLE 2.13 (continued)

MAP NUMBER	811	811^{e}	812	813	814	815	815
Date	1/7[illegible]	3/74	-	-	4/62	7/67	4/75
Reference^{a}	C	C	C	C	C	C	C
Units	mg/l	mg/l	mg/l	mg/l	ppm	ppm	mg/l
Temp.-C	240	240	-	-	-	>100	255
pH	6.6	6.10	6.5	4.0	5.30	5.3	-
Sp.Grav.	1.022	-	-	-	1.114	1.220	-
Sp.C.-µmho	-	22,697	-	-	24,736	-	-
TDS-sum	38,900	203,406	110,000	372,000†	153,300	266,560†	-
Ca	2,818	23,600	16,000	39,700	14,550	26,992	-
Mg	47	110	4,000	59	780	736	39
Na	8,562	47,300	20,400*	74,700	36,340	58,443	-
K	142	7,960	-	21,900	7,820	14,918	-
HCO_3	-	61.6	300	-	60	0	-
SO_4	-	<10	200	-	58	19	-
Cl	20,548	123,390	68,000	216,000	93,650	154,590	-
Ag	-	0.43	-	-	0	-	<3
Al	-	-	-	56	-	-	0.5
Ar	-	-	-	-	-	-	-
As	-	0.1870	-	-	10	10	100
B	-	-	-	518	210	332	92
Ba	-	55.7	-	241	540	-	2,600
Br	-	-	-	-	-	25	<2
Cd	-	1.12	-	-	-	-	<40
Cs	-	-	-	-	-	-	52
Co	-	-	-	-	-	-	<0.8
Cu	-	-	-	5.5	0	-	130
F	-	12	-	-	2.4	14	0.8
Fe	95	-	50	1,515	166	1,148	4,100
Hg	-	172	-	-	-	-	<3
Li	29	1.4	-	239	49	287	-
Mo	-	-	-	-	-	-	<8
Mn	9.8	-	4,000	1,480	410	1,025	7,500
NH_4	-	570	-	478	340	442	-
Ni	-	-	-	-	-	-	1,200
NO_3	-	1.05	1,050	41	-	5	-
Pb	-	36.2	-	155	80	-	500
PO_4	-	<0.8	-	-	-	-	-
Rb	-	50.4	-	-	-	-	5,300
SiO_2	108	435	-	560	350	90	-
Sr	-	102.4	-	482	360	434	4,800
Zn	-	283	-	740	-	-	6,100
Zr	-	-	-	-	-	-	24
H_2S	-	-	-	-	-	-	-
CO_2	-	-	-	-	-	-	-
Others	-	Be=0.08 Bi=5 Cr=0.3 Cs=250 Sb=6.7 Se=<0.001	-	Cr=0.8	Sb=0.2	I=13	-^{g,h}

*Na = K value

†TDS Residue on evaporation

(continued)

TABLE 2.13 (continued)

MAP NUMBER	816	816	818	818	818	818
Date	-	-	-	2/72	3/72	10/76
Reference[a]	C	P	P	H	H	C
Units	mg/l	ppm	ppm	mg/l	mg/l	ppm
Temp.-C	199	-	-	171	-	-
pH	4.0	-	6.2	6.4	6.2	5.71
Sp.Grav.	1.207	1.207	1.076	-	-	-
Sp.C.-μmho	-	-	-	-	-	-
TDS-sum	321,400	334,987	131,732	98,600†	167,000†	-
Ca	34,220	34,470	8,550	7,800	14,000	11,000
Mg	18	18	651	120	150	-
Na	66,000	70,000	49,257	30,000	55,000	23,000
K	24,400	24,000	2,881	3,200	7,200	5,080
HCO_3	-	-	-	-	-	-
SO_4	-	34	-	-	-	-
Cl	192,100	201,757	59,015	52,000	92,000	85,700
Ag	-	-	-	-	-	-
Al	-	-	-	-	-	-
Ar	-	-	-	-	-	-
As	-	-	-	-	-	-
B	540.5	149	-	-	-	-
Ba	-	-	-	-	-	-
Br	-	-	-	-	-	-
Cd	-	-	-	-	-	-
Cs	-	-	-	-	-	-
Co	-	-	-	-	-	-
Cu	-	-	-	-	-	-
F	-	-	-	-	-	-
Fe	4,130	4,200	84	150	270	64.8
Hg	-	-	-	-	-	-
Li	54	150	65	67	100	93
Mo	-	-	-	-	-	-
Mn	-	-	121	160	540	-
NH_4	-	-	-	-	-	-
Ni	-	-	-	-	-	-
NO_3	-	-	-	-	-	-
Pb	-	-	-	-	-	-
PO_4	-	-	-	-	-	-
Rb	-	-	-	-	-	-
SiO_2	5	5	112	150	200	-
Sr	-	-	-	-	-	513
Zn	-	-	-	-	-	-
Zr	-	-	-	-	-	-
H_2S	-	-	-	-	-	-
CO_2	-	-	-	-	-	-
Others	-	-	-	-	-	-

†TDS Residue on Evaporation at 180°C

(continued)

TABLE 2.13 (continued)

FOOTNOTES

[a] C = Cosner and Apps, 1977
H = Hardt and French, 1976
P = Palmer, 1975

[b] 340°C Temp. measured 6/64

[c] Average of several hundred analyses

[d] 181°C Temp. measured 1964

[e] Brine after steam flashed

[f] Unflashed brine

[g] Au=<3
Be=<0.05
Si=24
P=<0.08
S=390
Sc=<0.5
Ti=<8
V=<0.8
Ga=<2
Ge=5
Se=≦20
Y=<2
Nb=<2
Ru=<5
Rh=<2
Pd=≦5
In=<2
Sn=<20
Sb=<3
Te=≦5
I=<2
La=20
Ce=<1
Pr=<2
Nd=<3
Sm=<3
Eu=<5
Gd=<3
Tb=1
Dy=<3
Ho=<1
Er=<3

Tm=<1
Yb=<3
Lu=<1
HF=<3
Ta=≦8
W=<3
Re=<2
Os=<2
Ir=<2
Pt=<3
Tl=<2
Bi=<3
Th=<1
U=<1
Co=<0.8
Cr=<0.8

[h] The following radioactivity measurements are from O'Connell and Kaufmann, 1976. Sampling data are not specified.

^{222}Rn = 10,000 ± 42 pCi/l
^{226}Ra = 1,500 ± 71 pCi/l
^{234}U = <0.5 pCi/l
^{238}U = <0.41 pCi/l
^{230}Th = 0.3 ± 0.3 pCi/l
^{232}Th = <0.089 pCi/l

No. 808. Surface water analyses of 3.6 and 3.2 ppm, somewhat above the USPHS drinking water standard limit for fluoride, are reported for the Etna mud volcano and the Salton Sea, respectively.

Copper concentrations range from 2 to 130 mg/l for geothermal wells No. 41 and 815, respectively. All the copper analyses for geothermal wells are above the USPHS Drinking Water Standard recommendations, while all the surface waters appear to have acceptable copper contents. No copper data is available for other wells in the area.

Barium concentrations range from 3 mg/l in geothermal well No. 810 to 480 mg/l in geothermal well No. 806. All of the geothermal wells are above the USPHS limit of 1 mg/l for barium, while all the surface water analyses indicate acceptable barium values. No barium data is available for other wells in the area.

All the Salton Sea geothermal wells have iron contents higher than the USPHS drinking water recommendation of 0.3 mg/l. The reported range is from 0.7 mg/l in well No. 810 to 4,200 mg/l in well No. 816. All reported surface water samples have acceptable iron contents.

Lead contents much higher than the USPHS drinking water limit of 0.05 mg/l are reported for all the geothermal wells. They range from 60 mg/l in well No. 815 to 500 mg/l in another analysis of the same well. All of the reported surface water analyses have acceptable lead contents.

Reported manganese contents of Salton Sea geothermal wells range from 9.8 mg/l in well No. 811 to 7,500 mg/l in well No. 815. The USPHS limit is 0.05 mg/l and surface water samples at the Etna mud volcano and Poe Spring have manganese contents of 3.0 and 0.240 mg/l, respectively, while Salton Sea and Alamo River waters are below the USPHS manganese limit.

A silver content of 1.4 mg/l has been reported for well No. 808. This is considerably above the USPHS limit of 0.05 mg/l. All the surface water samples have acceptable silver content.

All the geothermal wells have excessive zinc contents ranging from 500 mg/l in well Nos. 41 and 801 to 6,100 mg/l in well No. 815. All of the reported surface water analyses are under the USPHS limit of 5 mg/l.

Based on a production fluid TDS concentration of 300,000 mg/l, the projected total amount of dissolved solids brought to the surface by potential geothermal production of the Salton Sea geothermal field is estimated to be 378 million kg/day (832 million lbs/day) (Table 2.7), or 4.1 x 10^{12} kg (9.1 x 10^{12} lbs) over the anticipated 30 years of power production. This would result from an estimated total brine mass production of about 1.26 billion kg/day (2.8 billion lbs/day) (Table 2.6). For chemical constituents with concentrations of 0.1 ppm or 100 ppm, the daily plant chemical throughput would be 126 and 126,000 kg/day (277 to 277,000 lbs/day), respectively (Table 2.7). It is anticipated, however, that the great majority of these chemical constituents would be injected back into the hydrologic unit they were removed from, thereby minimizing pollution or waste disposal problems.

2.3.4 Heber KGRA

Groundwater level contours (Loeltz, et al. 1975; Dutcher, et al. 1972) indicate that water entering the shallower water bearing strata in the eastern part of the Heber KGRA will flow to the west, then turn northward and flow toward the Salton Sea. Shallow groundwater entering the western portion of the Heber KGRA, from the Mexicali Valley, will only flow northward towards the Salton Sea. This means that any pollution escaping into the groundwater system will form northward-growing plumes and their shapes will depend on the number and relative location of the pollution sources.

A total of 22 wells are reported within the Heber KGRA (Table 2.14, Fig. 2.9). Seven of these are listed as heat reservoir or geothermal wells and six of them are being used. There are nine wells listed as observation wells, one test hole, one geothermal recharge well, two unused water withdrawal wells, and two are reported as destroyed. This compilation indicates that there is currently no domestic or agricultural use of groundwater in or within 1.6 km (1 mi) of the Heber KGRA.

Currently, all of the geothermal wells lie on an east-west trending line, about 8 km (5 mi) south of El Centro, all within the irrigated, agricultural area. They penetrate Quaternary lake deposits consisting of lacustrine silt, sand and clay on the surface and lie between mapped traces of the Imperial Fault and San Jacinto Fault. Additional fault traces in the Heber area, which would be more intimately related to the geothermal system, will probably be identified with further drilling and detailed geophysical investigations.

Available shallow groundwater analyses indicate a sodium chloride water with a small proportion of calcium, magnesium and sulfate (Table 2.15). The TDS range for these waters is from about 3,000 to 10,000 mg/l. Based on these few nongeothermal well water analyses there appears to be a shallow groundwater salinity gradient, with TDS contents increasing from about 3,000 mg/l in the southeastern corner of the Heber KGRA, and increasing to the north and west, to about 10,000 mg/l in the northwest corner of the KGRA. One deep nongeothermal well, USGS-LCRP 7

TABLE 2.14 DESCRIPTION OF WELLS IN AND WITHIN 1.6 KM (1 MI) OF HEBER KGRA*
(modified from Hardt and French, 1976)

MAP NUMBER	STATE NUMBER	OWNER OR NAME	YEAR DRILLED	OWNERSHIP	WATER USE	WELL USE	DIAM. (IN)	DEEPEST DEPTH (FT)	DEPTH CASED (FT)	DEPTH WELL (FT)	ALTITUDE OF LSD (FT)	WATER LEVEL (FT)	DATE WELL MEASURED	YIELD OF WELL (GPM)	CHEMICAL ANALYSES
297	16S/13E-13N01	USGS	1962	F	U	O	1	147	145	147	-25	11	2-62		x
298	16S/14E-27F01	CHEVRON GTW2	1975	N	G	H	8	3,000			-9				
299	16S/14E-27M01	CHEVRON GTW1	1975	N	G	H		3,400			-8				
300	16S/14E-28M01	A. TIMKEN 1	1945	N		Z		7,323			-15				
301	16S/14E-29G01	CHEVRON HULSE 1	1974	N	G	H		6,000			-16				
304	16S/14E-32K01	MAGMA HOLTZ 1	1972	N	G	W	8	5,147	3,765	5,107	10				x
307	16S/14E-34F01	CHEVRON GTW3	1975	N	G	H	8	4,000			-4				
308	16S/14E-34N01	USGS-USBR HEB.1	1975	F	Z	O	4	1,000	1,000		-4				
309	16S/15E-17L01	USGS	1962	F	U	O	1	162	145	147	-15	4	2-62		x
310	16S/15E-33D01	REPUBLIC	1975	P	G	H	10	6,067			12				
400	17S/14E-14Q01	W. LACHEMEYER	1961	P	U	O	1	162	71	73	-35	+4	5-61		x
401	17S/14E-14Q03	USGS LCRP 7	1962	F	U	O		1,000	260	330	-30				x
402	17S/14E-18M01	TEXACO JACOBS 1	1951	N		Z		7,505			-10				
403	17S/15E-10N01	I.I.D. DT 2	1958	W	U	T	8	500	110	450	22	9	10-60	90	x
404	17S/15E-16K01	I.I.D.	1961	W	U	O	1	162	150	152	20	9	5-61		x
405	17S/15E-16K02	I.I.D.	1961	W	U	O	1	10	8	10	18				
406	17S/16E-18P01		1961			O	1	162	150	152	25	+2	5-61		x
407	17S/16E-18Q01	USGS	1961	F	U	O	1	27	25	27	25	11	5-61		
500	16S/14E-33K01	CHEV NOWLIN PR1	1974	N	G	W		4,500			-5				
502	16S/14E-31J01	MAGMA HOLTZ 2	1972	N	G	R	8	5,000	3,906	4,945	10				x
503	16S/14E-32B01	C.B. JACKSON 1	1974	N	G	H					-10				x
504	16S/14E-33E01	J.D. JACKSON 1	1974	N	G	H					-8				x

*see Appendix II for explanation

TABLE 2.15 CHEMICAL ANALYSES OF WATER FROM NONGEOTHERMAL WELLS IN AND WITHIN 1.6 KM (1 MI) OF HEBER KGRA

MAP NUMBER	297	309	400	401	403	404	406
Date	7/62	7/62	1/62	3/62	4/58	1/62	1/62
Reference[a]	H	H	H	H	H	H	H
Units	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Temp.-C	26.7	26.7	-	-	-	-	-
pH	7.3	7.4	7.9	7.7	7.5	-	7.5
Sp.Grav.	-	-	-	-	-	-	-
Sp.C.-μmho	16,600	16,100	11,000	8,350	8,500	8,890	4,800
TDS-sum	9,540	9,410	6,980	4,920	5,610	5,410	3,020
Ca	362	376	448	175	253	244	103
Mg	211	214	261	122	143	161	48
Na	3,020*	2,920*	1,720*	1,480*	1,541	1,530*	953*
K	-	-	-	-	19	-	-
HCO_3	45	267	304	199	299	257	198
SO_4	175	400	1,350	800	1,450	850	538
Cl	5,750	5,350	3,040	2,240	2,040	2,490	1,280
Ag	-	-	-	-	-	-	-
Al	-	-	-	-	-	-	-
Ar	-	-	-	-	-	-	-
As	-	-	-	-	-	-	-
B	-	-	-	-	0.05	-	-
Ba	-	-	-	-	-	-	-
Br	-	-	-	-	-	-	-
Cd	-	-	-	-	-	-	-
Cs	-	-	-	-	-	-	-
Co	-	-	-	-	-	-	-
Cu	-	-	-	-	-	-	-
F	-	-	-	-	-	-	-
Fe	-	-	-	-	-	-	-
Hg	-	-	-	-	-	-	-
Li	-	-	-	-	-	-	-
Mo	-	-	-	-	-	-	-
Mn	-	-	-	-	-	-	-
NH_4	-	-	-	-	-	-	-
Ni	-	-	-	-	-	-	-
NO_3	-	-	-	-	-	-	-
Pb	-	-	-	-	-	-	-
PO_4	-	-	-	-	-	-	-
Rb	-	-	-	-	-	-	-
SiO_2	2	14	10	5	18	11	3
Sr	-	-	-	-	-	-	-
Zn	-	-	-	-	-	-	-
Zr	-	-	-	-	-	-	-
H_2S	-	-	-	-	-	-	-
CO_2	3.6	17	6.1	6.4	15	-	10
Others	-	-	-	-	-	-	-

[a] H = Hardt and French, 1976

*Na + K value

(No. 401), is 2,288 m (7,505 ft) deep and contains only 4,920 mg/l TDS. This is lower than the analyses of well No. 400, which is perforated from 21.6 to 22.2 m (71 to 73 ft), indicating 6,980 mg/l TDS. However, increased salinity at this depth may result from percolation through agriculturally used soils.

Analyses available for the deeper geothermal fluids indicate a TDS range from 11,800 to 19,000 mg/l. These minima and maxima for the Heber geothermal fluid both occur in Magma Holtz No. 1 (No. 304, Table 2.16). The lower value occurred in water sampled from 1,544 to 1,569 m (5,066 to 5,147 ft) depth interval, and the higher value in water from 1,202 to 1,227 m (3,945 to 4,026 ft) depth interval. With the limited number of analyses available it is impossible to tell if this difference in salt concentration is due to distinctly different waters in different hydrologic units, to variations in the chemistry of a "parent" geothermal fluid from related hydrologic units, to well and aquifer flow conditions, or to contamination. These geothermal waters are mainly sodium chloride in composition, some with the significant calcium content characteristic of the Salton Sea geothermal fluid.

The TDS content of all the Heber geothermal fluids is above the USPHS standards for drinking, irrigation or livestock use so the concentration of the major constituents will not be discussed further. The pH range of the geothermal fluids is from 5.8 to 7.1, the lower value being somewhat low for livestock or irrigation use.

Boron concentrations range from 4.8 mg/l in C. B. Jackson No. 1 (No. 503, Table 2.16) to 8 mg/l in Magma Holtz No. 2 (No. 502, Table 2.16). All the boron concentrations reported for geothermal wells are above the USPHS irrigation water limits.

Analyses for copper indicate a range from 0.2 mg/l reported in Chevron Nowlin No. 1 (No. 500, Table 2.16) to 0.4 mg/l in three other Heber geothermal wells. These values are within the USPHS drinking water standards. Fluoride concentrations are reported to be from 0.6 to 1.6 mg/l for Heber geothermal wells, which are below the USPHS drinking water standards. Iron concentrations in Heber geothermal water from 0.9 to 20 mg/l in Chevron Nowlin No. 1 (No. 500) and C. B. Jackson No. 1 (No. 503), respectively, are all above the USPHS drinking water standards. Manganese values from 0.9 to 1.9 mg/l have been reported from Heber geothermal water. The USPHS drinking water standard for manganese is 0.05 mg/l. Zinc concentrations are reported to be from 0.1 to 0.5 mg/l, which are well within the 5 mg/l drinking water standard.

The projected total amount of dissolved solids brought to the surface by geothermal production at Heber is estimated to

TABLE 2.16 CHEMICAL ANALYSES OF GEOTHERMAL FLUIDS IN AND WITHIN 1.6 KM (1 MI) OF HEBER KGRA

MAP NUMBER	500	304[b]	304[b]	502[c]	502[c]	503	504
Date	-	-	3/72	6/72	-	-	-
Reference[a]	G	G	H	H	G	G	G
Units	ppm	ppm	mg/l	mg/l	ppm	ppm	ppm
Temp.-C	-	-	-	-	-	-	-
pH	7.1	-	6.4	6.4	7.4	5.8	6.5
Sp.Grav.	-	-	-	-	-	-	-
Sp.C.-μmho	-	-	-	-	-	-	-
TDS-sum	14,100	13,168	11,900†	12,800†	16,330	15,430	15,275
Ca	880	1,062	780	860	1,062	891	781
Mg	2.4	5.6	30	4.7	23	4.7	3.8
Na	3,600	5,500	3,700	3,200	4,720	4,688	4,563
K	360	220	230	220	231	181	197
HCO_3	20	-	-	-	-	-	-
SO_4	100	100	-	-	148	152	150
Cl	9,000	7,420	6,300	6,500	8,242	8,320	8,076
Ag	-	-	-	-	-	-	-
Al	0.04	15	-	-	12	0.5	18
Ar	-	-	-	-	-	-	-
As	-	-	-	-	-	-	-
B	4.8	4.1	-	-	8	4.8	5.2
Ba	-	6	-	-	3	3	3
Br	-	-	-	-	-	-	-
Cd	-	-	-	-	-	-	-
Cs	-	-	-	-	-	-	-
Co	-	-	-	-	-	-	-
Cu	0.2	0.5	-	-	0.4	0.4	0.4
F	1.6	1.7	-	-	1.5	0.9	0.6
Fe	0.9	15	-	-	5	20	10
Hg	-	-	-	-	-	-	-
Li	6.6	4	3.7	3.2	4.1	2.8	3.4
Mo	-	-	-	-	-	-	-
Mn	-	0.9	-	-	0.9	1.3	1.9
NH_4	-	-	-	-	-	-	-
Ni	-	-	-	-	-	-	-
NO_3	-	-	-	-	-	-	-
Pb	0.1	1.6	-	-	0.6	0.6	0.9
PO_4	-	-	-	-	-	-	-
Rb	-	-	-	-	-	-	-
SiO_2	120	268	98	75	187	267	268
Sr	-	37	-	-	42	32	36
Zn	0.68	0.3	-	-	0.1	0.4	0.5
Zr	-	-	-	-	-	-	-
H_2S	-	-	-	-	-	-	-
CO_2	-	-	-	-	-	-	-
Others	L1=4						

†TDS Residue on evaporation at 180°C

[a] G = Geonomics, 1976

H = Hardt and French, 1976

[b] 170°C Temp. measured 5/72

[c] 163°C Temp. measured 7/72

be 37.8 million kg/day (83.3 million lb/day) (Table 2.7) or 414 billion kg (913 billion lb) over the anticipated 30 years of power production, based on an estimated average TDS content of 15,000 mg/l for the Heber geothermal fluid. This will result from estimated brine mass production of 2.52 billion kg/day (5.56 billion lb/day) (Table 2.6). For chemical constituents with concentrations of 0.1 ppm or 100 ppm, the daily plant chemical throughput would be 556 and 556,000 lbs, respectively (Table 2.7). It is anticipated, however, that the great majority of these chemical constituents would be injected back into the hydrologic unit they were removed from, thereby minimizing pollution or waste disposal problems.

2.3.5 Brawley KGRA

It appears that there is very little, if any, non-geothermal groundwater use in or near the Brawley KGRA. The shallow sediments here have very low permeability and the groundwater generally is too saline for most drinking, irrigation or livestock uses. Therefore, the emphasis in this area would be on maintaining natural groundwater conditions and preventing the highly saline geothermal brines from escaping to the surface.

There are only seven wells listed in or within the Brawley KGRA (Table 2.17, Fig. 2.10). Six of these are geothermal, observation or petroleum exploration wells and only one (No. 147) is listed as being domestically used. The one well that has reported domestic use is also quite warm (51.4°C [124.5°F]) and is included in the nongeothermal well chemical analysis table (Table 2.18). This well is about 8 km (5 mi) up-gradient from the geothermal wells and it would be unlikely that potential pollutant plumes would extend this far up-gradient.

At the surface, all of these wells penetrate Quaternary lake deposits. The geothermal wells are located east of the concealed trace of the Brawley Fault, defined by Meidav, et al. (1976) and Hill, et al. (1975a), and west of the projection of the concealed trace of the Fondo Fault, defined by Meidav, et al. (1976). These geothermal wells probably tap a reservoir genetically related to part of the complexly faulted Salton Trough Fault Zone (Geonomics, in press), lying between the mapped traces of the Fondo and Brawley Faults, but there is not enough data available yet to substantiate this speculation.

Although the few published groundwater analyses in the Brawley KGRA area (Table 2.18) show TDS contents from 3,120 mg/l ("thermal" well, No. 147) to 15,200 mg/l (USGS observation well, No. 96) it is reported in the geothermal industry that the geothermal fluid from the Brawley geothermal field will contain TDS on the order of 85,000 to 100,000 mg/l. This is much more concentrated than any of the other available analyses and it would also contain considerably more trace elements. Therefore,

TABLE 2.17 DESCRIPTION OF WELLS IN AND WITHIN 1.6 KM (1 MI) OF DUNES, GLAMIS AND BRAWLEY KGRAS* (modified from Hardt and French, 1976)

MAP NUM-BER	STATE NUMBER	OWNER OR NAME	YEAR DRILLED	OWNERSHIP	WATER USE	WELL USE	DIAM. (IN)	DEEPEST DEPTH (FT)	DEPTH CASED (FT)	DEPTH WELL (FT)	ALTI-TUDE OF LSD (FT)	WATER LEVEL (FT)	DATE WELL MEA-SURED	YIELD OF WELL (GPM)	CHEMICAL ANALYSES
DUNES															
233	15S/19E-19H01	USGS	1964	F	U	O	1	177	155	157	138	43	3-64		
234	15S/19E-28N01	USGS	1964	F	U	O	1	172	153	155	145	43	2-64		x
235	15S/19E-33C01	USBR 121	1971	F	Z	T	6	562			155	41	3-71		
236	15S/19E-33D01	USBR 117	1971	F	Z	T	8	563			150				
237	15S/19E-33G01	USBR 120	1971	F	Z	T	6	562			150				
239	15S/19E-33L02	USBR 115	1971	F	Z	T	6	375			142	24	2-71		
240	15S/19E-33N01	USBR 118	1971	F	Z	T	6	542			140	28	2-71		
241	15S/19E-33R01	USGS	1964	F	U	O	1	177	155	157	143	35	3-64		x
242	15S/19E-33R02	USBR 119	1971	F	Z	T	6	562			143	33	3-71		
367	16S/19E-02N01	USGS	1961	F	U	O	1	142	134	136	154	40	10-61		x
600	15S/19E-33L01	CDWR DUNES 1	1972	S	G	H	4	2,007	340	1,918	142				x
GLAMIS															
133	13S/17E-35P01	USGS	1961	F	U	O	1	142	25	27	110	7	10-61		x
134	13S/17E-35P02	USGS	1962	F	U	T		162	158	160	110	12	3-62		x
135	13S/18E-33A01	A. SMITH	1972	P	H	W	8	681	520	680	330	227	4-72		x
BRAWLEY															
79	12S/14E-21J01	USGS	1962	F	U	O	1	152	145	147	-176	0	2-62		x
92	13S/14E-09R01	VEYSEY #1	1945	N		P	12	8,350			-150				
93	13S/14E-15M01	UNION VEYSEY 1	1975	N	N	H	12	8,385	5,200		-170				
94	13S/14E-16P01	UNION TOW 1	1975	N	N	H					-141				
95	13S/14E-21G01	UNION VEYSEY 2	1975	N	N	H		5,921			-140				
96	13S/14E-21K01	USGS	1962	F	U	O	1	152	145	147	-160	+8	5-62		x
147	14S/15E-06B01	N. FIFIELD	1965	P	H	W	2	1,290			-132	F	2-62		x

*see Appendix II for explanation

TABLE 2.18 CHEMICAL ANALYSES OF WATER FROM NONGEOTHERMAL WELLS IN AND WITHIN 1.6 KM (1 MI) OF DUNES, GLAMIS AND BRAWLEY KGRAS

	Dunes			Glamis		
MAP NUMBER	367	234	241	133	134	135
Date	2/62	1/62	3/64	10/61	5/62	4/72
Reference[a]	H	H	H	H	H	H
Units	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Temp.-C	-	41.1	39.4	-	-	-
pH	7.8	7.8	8.6	7.8	7.8	6.8
Sp.Grav.	-	-	-	-	-	-
Sp.C.-µmho	1,170	5,060	3,180	1,270	1,150	-
TDS-sum	751	2,760	1,710	850	709	-
Ca	65	143	111	97	73	79
Mg	22	5.6	10	30	32	-
Na	153*	885*	505*	144*	121*	1,135
K	-	-	-	-	-	86
HCO_3	136	94	98	163	126	-
SO_4	316	225	233	362	300	-
Cl	102	1,410	775	119	113	-
Ag	-	-	-	-	-	-
Al	-	-	-	-	-	-
Ar	-	-	-	-	-	-
As	-	-	-	-	-	-
B	-	-	-	-	-	-
Ba	-	-	-	-	-	-
Br	-	-	-	-	-	-
Cd	-	-	-	-	-	-
Cs	-	-	-	-	-	-
Co	-	-	-	-	-	-
Cu	-	-	-	-	-	-
F	-	1.9	1	-	-	-
Fe	-	-	-	-	-	-
Hg	-	-	-	-	-	-
Li	-	-	-	-	-	-
Mo	-	-	-	-	-	-
Mn	-	-	-	-	-	-
NH_4	-	-	-	-	-	-
Ni	-	-	-	-	-	-
NO_3	-	-	-	-	-	-
Pb	-	-	-	-	-	-
PO_4	-	-	-	-	-	-
Rb	-	-	-	-	-	-
SiO_2	2.5	39	29	16	7	-
Sr	-	-	-	-	-	-
Zn	-	-	-	-	-	-
Zr	-	-	-	-	-	-
H_2S	-	-	-	-	-	-
CO_2	3.4	2.4	0.4	4.1	3.2	-[b]
Others	-	-	-	-	-	-

*Na + K value

(continued)

TABLE 2.18 (continued)

	Brawley		
MAP NUMBER	79	96	147
Date	7/62	7/62	12/70
Reference[a]	H	H	H
Units	mg/l	mg/l	mg/l
Temp.-C	25.6	-	51.4
pH	7.4	7.1	8.4
Sp.Grav.	-	-	-
Sp.C.-μmho	19,800	16,500	5,550
TDS-sum	15,200	10,300	3,120
Ca	810	930	40
Mg	822	608	15
Na	3,400*	1,990*	1,200
K	-	-	6.9
HCO_3	408	294	420
SO_4	4,050	1,250	310
Cl	5,850	5,400	1,300
Ag	-	-	-
Al	-	-	-
Ar	-	-	-
As	-	-	-
B	-	-	2
Ba	-	-	-
Br	-	-	-
Cd	-	-	-
Cs	-	-	-
Co	-	-	-
Cu	-	-	-
F	-	-	1
Fe	-	-	0.32
Hg	-	-	-
Li	-	-	0.23
Mo	-	-	-
Mn	-	-	-
NH_4	-	-	3.2
Ni	-	-	-
NO_3	-	-	-
Pb	-	-	-
PO_4	-	-	-
Rb	-	-	-
SiO_2	18	15	30
Sr	-	-	1.2
Zn	-	-	-
Zr	-	-	-
H_2S	-	-	-
CO_2	26	37	17
Others	-	-	-[c]

*Na + K value

(continued)

TABLE 2.18 (continued)

FOOTNOTES

[a] Hardt and French, 1976

[b] The following radioactivity measurements are from O'Connell and Kaufmann, 1976. Sampling data are not specified.

^{222}Rn=1100 ± 55 pCi/l
^{226}Ra=0.85 ± 0.14 pCi/l

[c] The following radioactivity measurements are from O'Connell and Kaufmann, 1976. Sampling data are not specified.

^{222}Rn=300 ± 35 pCi/l
^{226}Ra=0.37 ± 0.095 pCi/l
^{234}U=0.30 ± 0.07 pCi/l
^{248}U=0.18 ± 0.05 pCi/l
^{230}Th=0.64 ± 0.23 pCi/l
^{232}Th=<0.10 pCi/l

it would be misleading to discuss the one "thermal" fluid analysis we have in the Brawley area as representative of the Brawley geothermal fluid. It would be much more realistic to say that it will be a highly saline brine, probably similar in character to the Salton Sea geothermal fluid, with many trace element concentrations exceeding USPHS drinking, irrigation and livestock standards and it would be harmful for this fluid to escape into the ground or surface water systems of Imperial Valley.

The Brawley geothermal field lies along the approximate location of a northerly trending rise in groundwater salinity discussed by Geonomics (in press). Shallow groundwater along this trend would be expected to have much higher salinities than shallow groundwater to the east, and somewhat higher than in areas to the west.

The two available shallow groundwater analyses have chemical characteristics similar to those of Salton Sea water, but less concentrated. Well No. 96, a USGS observation well located in the south-central part of the Brawley KGRA (Fig. 2.10), with a 44.2 to 44.8 m (145 to 147 ft) perforated interval, has a TDS content of 10,300 mg/l. The proportions of the major constituents show this to be a sodium chloride water with notable quantities of calcium, sulfate and magnesium. These characteristics suggest a possible mixing of a sodium chloride calcium Salton Sea geothermal fluid with the sodium chloride sulfate magnesium groundwater commonly found south of the Salton Sea. Groundwater from well No. 79, a USGS observation well located just north of the Brawley KGRA (Fig. 2.10), has a TDS content of 15,200 mg/l and is typical of the sodium chloride sulfate magnesium groundwater just mentioned. This well is also perforated between 44.2 and 44.8 m (145 to 147 ft). No trace element data are available for the observation wells.

The total daily brine mass estimated to be produced utilizing Brawley's full geothermal capacity, estimated at 330 MWe for 30 years, will be 68 million kg/day (150 million lb/day) (Table 2.6). For a chemical constituent with a concentration of 1 ppm, 680 kg (1,500 lb) day will be produced; for a concentration of 1,000 ppm, 680,000 kg/day (1.5 million lb/day) will be produced. Most of these quantities will, however, be injected back into the producing aquifer.

2.3.6 Dunes and Glamis KGRAs

The water pollution discussion for the Dunes and Glamis areas will be limited due to: 1) the virtually nonexistent groundwater use, 2) the lack of groundwater data, and 3) the previously discussed extremely low probability of geothermal development in these areas.

Dunes KGRA--

There are currently ten wells located in the Dunes KGRA (Table 2.17, Fig. 2.9). Nine are test or observation wells and the remaining one is a geothermal test hole. There is no known groundwater use in this area.

The Dunes wells are drilled on both sides of the contact between Quaternary alluvium, on the western side of the San Andreas Fault and Quaternary windblown sand east of the San Andreas Fault. Minor occurrences of Quaternary lake deposits appear along this contact. The wells are clustered near the intersection of an unnamed fault and the trace of the San Andreas Fault. The unnamed trace trends northwest-southeast, and is about 30 km (19 mi) (Loeltz, et al. 1975).

Shallow groundwater flows northwesterly through the Dunes geothermal area, but shallow groundwater levels have increased significantly in this area since operation of the Coachella Canal, beginning in the 1940s. (See discussion in Geonomics, in press).

Three chemical analyses for the Dunes CDWR No. 1 geothermal test well are shown in Table 2.19 (Nos. 600A, B and C) and analyses for three nongeothermal wells are shown on Table 2.18. The TDS concentrations from different perforated intervals in the geothermal well range from 1,410 to 2,530 mg/l and from 751 to 2,760 mg/l in the nongeothermal wells. It should be noted that the geothermal samples may not be representative of the geothermal fluid in the reservoir since these were all bailed samples. If we accept the samples then we may note salinity decreasing with depth for the geothermal well: from 2,530 mg/l in a 117 m (384 ft) sample to 1,410 mg/l in a 575 m (1,886 ft) sample. This water has relatively low salinity compared to other Imperial Valley geothermal waters and, in fact, is less saline than much of the natural groundwater in the valley. These are sodium chloride waters with high sulfate content suggestive of mixing with other waters or of Colorado River water reacting with subsurface sediments. The geothermal sample from 575 m (1,886 ft) depth (No. 600C) is within 2 km (1.2 mi) of the Coachella Canal and has chemical characteristics similar to evaporated Colorado River water.

The proportions of the major chemical constituents apparently change more significantly than the change in TDS contents. Shallow groundwater samples No. 234 and 241 are basically sodium chloride waters with some calcium and sulfate. These samples are probably more representative of natural groundwater character than sample No. 367 directly beneath the Coachella Canal, which contains 751 mg/l TDS and has the very high sulfate with high sodium, chloride, calcium and bicarbonate water characteristic of the Colorado River.

TABLE 2.19 CHEMICAL ANALYSES OF GEOTHERMAL FLUIDS IN AND WITHIN 1.6 KM (1 MI) OF DUNES KGRA

MAP NUMBER	600C[b]	600B[c]	600A[d]
Date	-	-	-
Reference[a]	CC	CC	CC
Units	ppm	ppm	ppm
Temp.-C	88	92	92
pH	8.4	-	8.5
Sp.Grav.	-	-	-
Sp.C.-µmho	-	-	-
TDS-sum	1,410	2,190	2,530
Ca	201	23	37
Mg	6.1	3	9.4
Na	206	686	800
K	23	94	84
HCO_3	-	-	-
SO_4	416	675	605
Cl	188	570	854
Ag	-	-	-
Al	-	-	-
Ar	-	-	-
As	0	0	0.01
B	0.6	1.2	1.9
Ba	0.3	0.2	0.2
Br	0.66	3	2
Cd	0	0	0
Cs	-	-	-
Co	-	-	-
Cu	0.07	0.12	0.15
F	1.4	10	8
Fe	0.16	0.05	0.12
Hg	-	-	-
Li	0.13	0.32	0.53
Mo	-	-	-
Mn	0	0	0
NH_4	-	-	-
Ni	0	0	0
NO_3	-	-	-
Pb	0.04	0.05	0.11
PO_4	-	-	-
Rb	-	-	-
SiO_2	19	1.9	29
Sr	-	-	-
Zn	0.6	0.22	0.09
Zr	-	-	-
H_2S	-	-	-
CO_2	-	-	-
Others	I=0.021	I=0.019	I=0.023

(continued)

TABLE 2.19 (continued)

FOOTNOTES

[a] CC = Coplen, et al. (1973)

[b] Perforation interval 572-584 m (1,876-1,916 ft) bailed from 575 m (1,886 ft)

[c] Perforation interval 259-271 m (850-872 ft) bailed from 276 m (905 ft)

[d] Perforation interval 104-116 m (341-380 ft) bailed from 117 m (384 ft)

No estimates of potential quantities of pollutant production have been made for the Dunes KGRA since geothermal development is not currently foreseen.

Glamis KGRA--

Only three wells are listed in the Glamis KGRA (Table 2.17), and none are geothermal wells. Two of these are USGS test (No. 134) and observation (No. 133) wells in the western part of the designated KGRA, near the Coachella Canal, and one is a domestic well (No. 135) located in the eastern portion of the KGRA. The USGS wells penetrate Quaternary alluvium at the surface and are just west of the trace of the San Andreas Fault. They are perforated in the shallower hydrologic unit between 47 and 48 m (154 and 157 ft) and between 48 and 49 m (157 and 161 ft), respectively. The domestic well is located on Quaternary alluvium in an area traversed by three mapped traces of the Sand Hills - Algodones Fault (Loeltz, et al. 1975; Jennings, 1967; Jennings, 1975). This well perforates the intermediate depth hydrologic unit from 158 to 207 m (520 to 680 ft).

The two shallower USGS wells are drilled essentially beneath the Coachella Canal; the water from these wells is almost pure Colorado River water, probably derived from downward percolation from the canal. These waters have the high proportion of sulfate characteristic of Colorado River water and TDS contents of 850 and 709 mg/l, respectively.

The TDS content is not available for the domestic well, but it has a sodium plus potassium content of 1,211 mg/l, which is about ten times the amount in the lower salinity well mentioned above. No trace element analyses are available for any of the well water. So it seems that the two USGS wells have water suitable for drinking or other uses, but it is probably more representative of Coachella Canal water than natural groundwater. The high sodium plus potassium content of the domestic well suggests that this water will not be suitable for drinking or irrigation use.

Groundwater elevation contours (Loeltz, et al. 1975) indicate that groundwater flows northwest through the Glamis KGRA towards the Salton Sea.

2.4 SEISMICITY

A potentially significant subsurface environmental effect of geothermal development is seismicity induced by fluid extraction and withdrawal. Currently the Imperial Valley is among the most seismically active areas in the United States. This naturally occurring high level of macro- and micro-seismicity makes it difficult to differentiate from seismicity potentially induced by extraction and injection of geothermal fluids.

Presently, extensive and exhaustive baseline seismicity data must be collected prior to development to provide a detailed basis for comparison of pre- and post-development seismic activity. To this end, the following discussion will outline historical seismicity, seismic risk, ongoing programs that are currently collecting baseline seismicity data, and potential induced seismicity for Imperial Valley.

2.4.1 Summary of Baseline Seismicity and Seismic Risk

The Salton Trough in general, and the Imperial Valley in particular, are characterized by a high level of seismic activity and a large amount of strain release. Seismicity within Imperial Valley is characterized by both swarm activity and main shock-aftershock sequences (Hileman, et al. 1973; Richter, 1958). Richter reports that 12 earthquakes of magnitude 6 or greater have occurred in the Salton Trough since 1900, and nine earthquakes greater than magnitude 6.7 have occurred since 1850. High levels of microseismic activity have been recorded in the Salton Sea, Brawley and East Mesa KGRAs (Hill, et al. 1975a).

The geographic distribution of instrumentally recorded earthquakes from 1932 through 1975 shows the density of epicenters to be much greater in the western part of the valley, especially along the San Jacinto Fault Zone. A minimal number of epicenters are located along the San Andreas Fault Zone in the eastern part of the valley (see Geonomics, in press, Plate 2.10). Although earthquakes are generally correlated with faults, this is not apparent from the distribution of these historic macroseismic events. The apparent scatter in epicenter locations is probably due to inaccurate epicenter locations, currently unidentified fault trace locations, possibly dipping fault planes, and the fact that much strain may be released through fault creep.

Earthquakes occurring in the San Andreas Fault System typically have focal depths of 5 to 8 km (3 to 5 mi), which is the basement-sediment interface. A limiting depth for hypocenters in southern California is about 12 to 15 km (7 to 9 mi), but in geothermal areas of Imperial Valley this limiting depth is about 8 km (5 mi), due to higher geothermal temperatures closer to the surface which allow plastic, as opposed to brittle, deformation (Johnson and Hadley, 1976).

Microseismic activity in the valley has been documented on several occasions (e.g., Hill, et al. 1975a, 1975b; Sharp, 1976; Johnson and Hadley, 1976; Combs and Hadley, 1977). In most cases the locations of these microseismic events are accurate enough to define fault traces correlated with the activity.

A microseismic net was operating for five weeks during the summer of 1973 in the East Mesa KGRA in order to establish back-

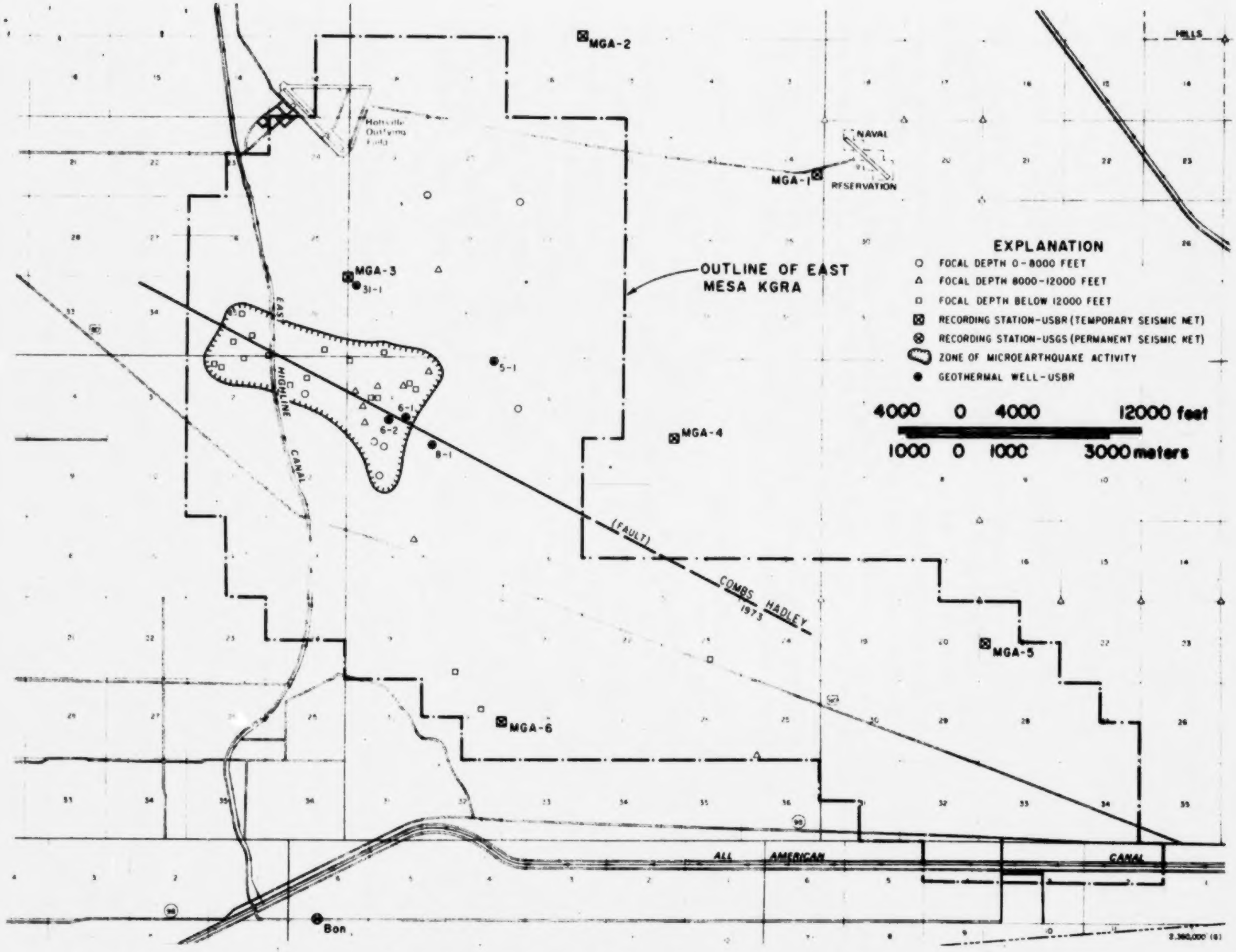

EXPLANATION
FOCAL DEPTH 0-8000 FEET
FOCAL DEPTH 8000-12000 FEET
FOCAL DEPTH BELOW 12000 FEET
RECORDING STATION-USBR (TEMPORARY SEISMIC NET)
RECORDING STATION-USGS (PERMANENT SEISMIC NET)
ZONE OF MICROEARTHQUAKE ACTIVITY
GEOTHERMAL WELL-USBR
4000 0 4000 12000 feet
1000 0 1000 3000 meters
OUTLINE OF EAST MESA KGRA
MGA-1
MGA-2
MGA-3
MGA-4
MGA-5
MGA-6
31-1
5-1
6-1
6-2
8-1
(FAULT)
COMBS HADLEY 1973
NAVAL RESERVATION
HILLS
Holtville Outlying Field
EAST HIGHLINE CANAL
ALL AMERICAN CANAL
Bon

Figure 2.11 Microearthquake epicenters recorded in East Mesa, June 10 to July 15, 1973 (U.S. Bureau of Reclamation, 1974)

ground seismicity prior to geothermal power development (Combs and Hadley, 1977). The recording station and epicenter locations from this survey are shown in Fig. 2.11. This study established that the occurrence of microseismic events is not constant with time. On the majority of days, only one or two locatable events occurred; while two-to three-day swarms of up to 100 distinct local events per day occurred twice during this recording period. Additionally, hundreds of smaller events (nanoearthquakes), some clustered in swarms, were recorded by each seismograph. More than half the events had focal depths between the approximate depths to basement of 4 km and 8 km (2.5 to 5 mi).

Epicenters located from the USGS-Cal Tech seismograph network during the period between June 1973 and May 1974 are shown in Fig. 2.12 (Hill, et al. 1975a). This figure shows the location of all events recorded at four or more stations in the net. Although many magnitude 1 earthquakes are included, coverage is only considered complete for events of magnitude 2 or greater, due to the high seismic noise levels in the cultivated areas of the valley.

This survey shows a linear seismicity trend in the central part of the valley, along the Imperial and Brawley Faults. Marked concentrations of events occurred along the Imperial Fault, directly east of El Centro, and in the north and south portions of the Brawley geothermal field. Smaller concentrations occurred near Obsidian Buttes, on the western portion of the Salton Sea geothermal field, and along the San Jacinto Fault Zone. Most of the events in this study occurred in four swarms between June 20 and July 17, 1973; otherwise, the seismic activity developed in a fairly uniform manner (Hill, et al. 1975a).

Another example of swarm activity in Imperial Valley is reported by Johnson and Hadley (1976) from January 23 to 31, 1975 in the Brawley area (Fig. 2.13). The swarm was most intense for four days, with 75 events of 3.0 to 4.7 local magnitude along a 12 km (7.5 mi) zone. Hypocenters were located for 264 earthquakes with local magnitudes greater than or equal to 1.5. Basement depth here is about 6 km (3.7 mi), and hypocentral depths ranged from 4 to 8 km (2.5 to 5 mi),as Combs and Hadley (1977) found in East Mesa.

A swarm of over 400 earthquakes occurred near Calipatria from November 3 to 8, 1976 (Porcella and Nielson, 1977). Seven events of local magnitude equal to or greater than 4.0 occurred within an eight-and-a-half-hour period on November 4, 1976 (Fig. 2.14). These earthquakes, as well as two local magnitude 3.8 and 3.9 events on April 26 and 14, 1976, respectively, were reported in reference to the national strong motion accelerograph network. The strong motion accelerograph network program

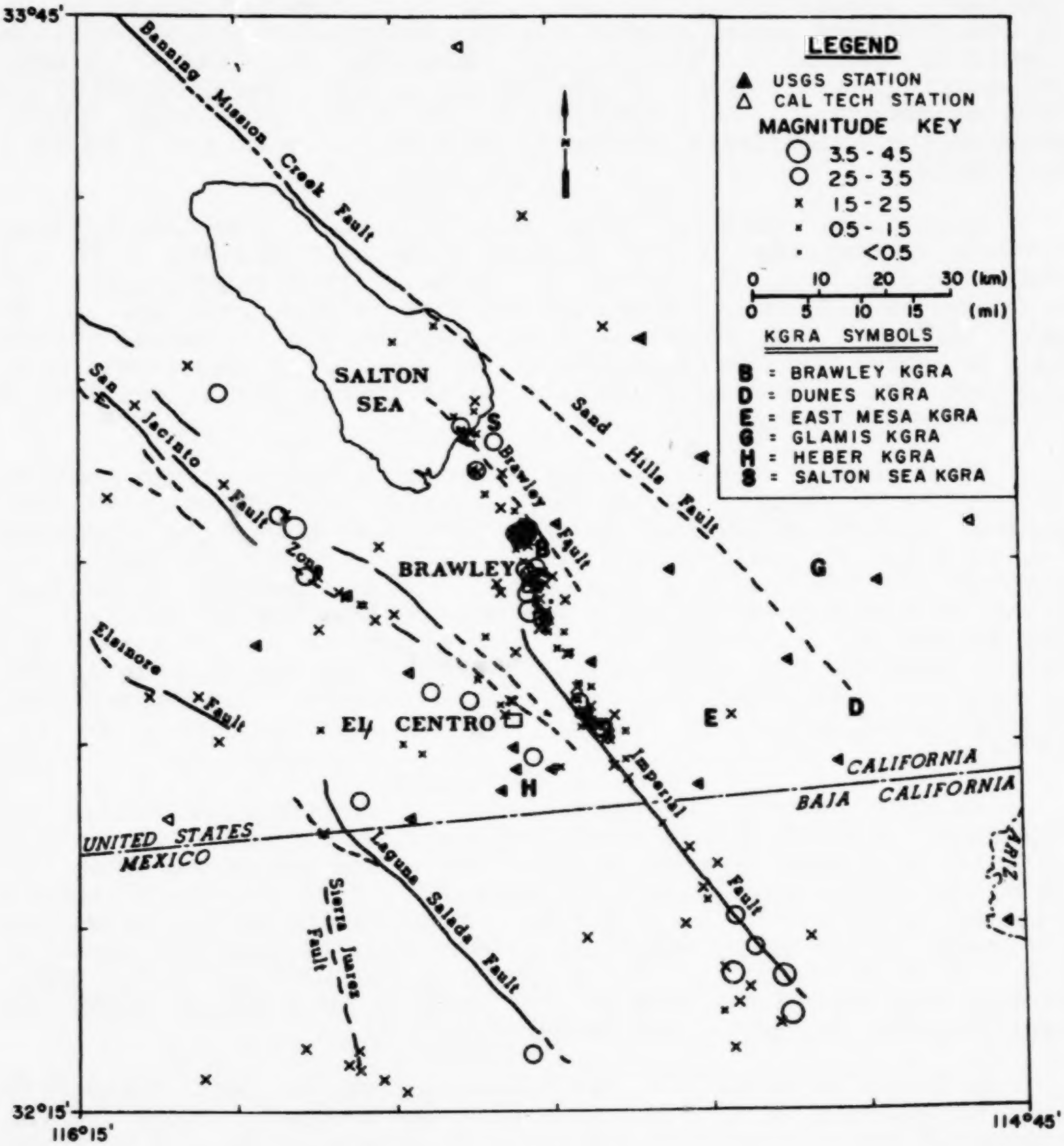
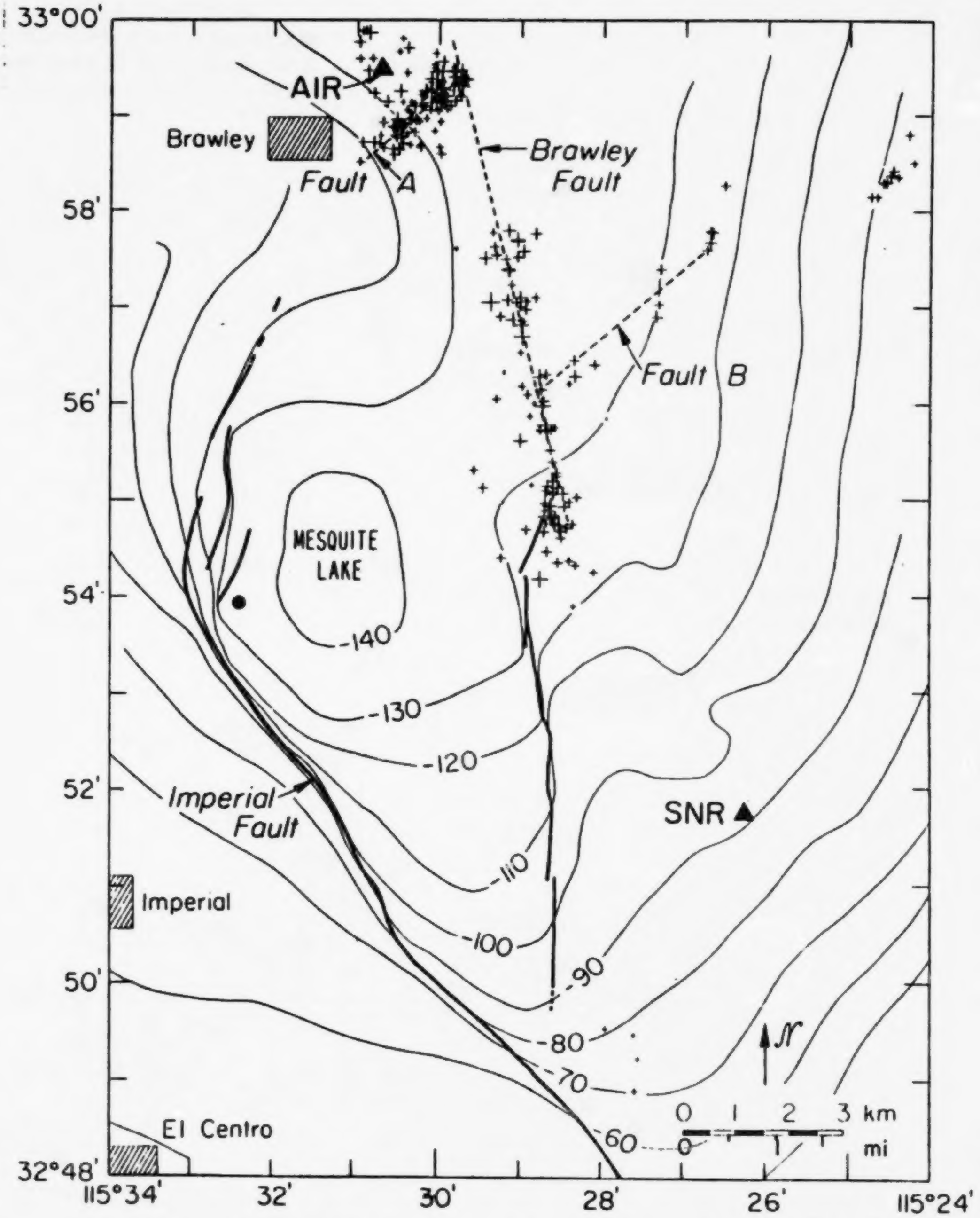

33°45'
32°15'
116°15'
114°45'
LEGEND
▲ USGS STATION
△ CAL TECH STATION
MAGNITUDE KEY
3.5 - 4.5
2.5 - 3.5
1.5 - 2.5
0.5 - 1.5
<0.5
0 10 20 30 (km)
0 5 10 15 (mi)
KGRA SYMBOLS
B = BRAWLEY KGRA
D = DUNES KGRA
E = EAST MESA KGRA
G = GLAMIS KGRA
H = HEBER KGRA
S = SALTON SEA KGRA
N
Banning Mission Creek Fault
SALTON SEA
S
Brawley Fault
Sand Hills Fault
San Jacinto Fault
Zone
BRAWLEY
B
G
Elsinore Fault
EL CENTRO
E
D
H
Imperial Fault
CALIFORNIA
BAJA CALIFORNIA
UNITED STATES
MEXICO
Laguna Salada Fault
Sierra Juarez Fault
ARIZ

Figure 2.12 Location of seismograph stations and earthquake epicenters in the Imperial Valley, June 1, 1973-May 31, 1974 (Hill, et al. 1975a)


33°00'
AIR
Brawley
Fault
A
Brawley
Fault
58'
Fault
B
56'
MESQUITE
LAKE
54'
-140
-130
-120
52'
Imperial
Fault
SNR
-110
Imperial
-100
50'
-90
-80
-70
0 1 2 3 km
El Centro
-60
0 1 mi
32°48'
115°34'
32'
30'
28'
26'
115°24'

(See Fig. 2.15 for location and explanation)

Figure 2.13 Epicenters of earthquakes of the Brawley swarm, January, 1975 (Johnson and Hadley, 1976)

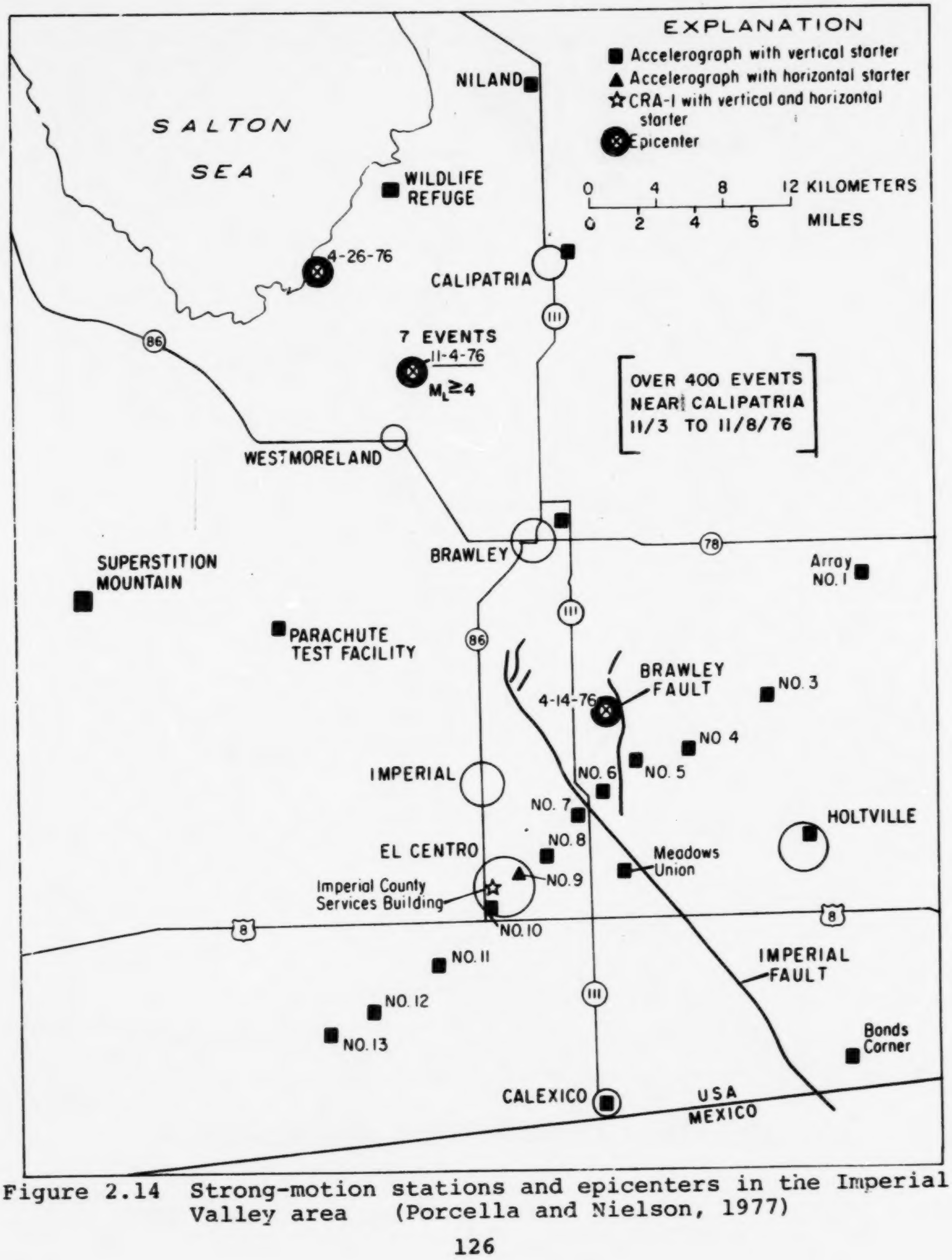

EXPLANATION
■ Accelerograph with vertical starter
▲ Accelerograph with horizontal starter
☆ CRA-1 with vertical and horizontal starter
Epicenter
0 4 8 12 KILOMETERS
0 2 4 6 MILES
SALTON SEA
NILAND
WILDLIFE REFUGE
4-26-76
CALIPATRIA
111
86
7 EVENTS
11-4-76
$M_L \geq 4$
OVER 400 EVENTS NEAR CALIPATRIA 11/3 TO 11/8/76
WESTMORELAND
BRAWLEY
78
Array NO. 1
SUPERSTITION MOUNTAIN
PARACHUTE TEST FACILITY
BRAWLEY FAULT
4-14-76
NO. 3
NO 4
NO. 5
NO. 6
NO. 7
NO. 8
NO. 9
NO. 10
NO. 11
NO. 12
NO. 13
IMPERIAL
HOLTVILLE
EL CENTRO
Meadows Union
Imperial County Services Building
8
IMPERIAL FAULT
Bonds Corner
CALEXICO
USA
MEXICO

Figure 2.14 Strong-motion stations and epicenters in the Imperial Valley area (Porcella and Nielson, 1977)

provides critical information on ground response that is applied to the development of earthquake-resistant engineering design.

Microseismic Monitoring Networks--

USGS, in cooperation with Cal Tech, established a regional 18-station telemetered seismograph network in 1973 in Imperial Valley (Hill, et al. 1975a). This network was specifically set up to record earthquakes related to geothermal phenomena. The location of these stations is shown by triangles in Fig. 2.15. In October, 1976 the USGS installed six seismometers in the Salton Sea geothermal field region in conjunction with the ERDA/LLL Imperial Valley Environmental Project (Phelps and Anspaugh, 1976). These seismometers will also be incorporated into the USGS telemetered network. Their locations are shown by black circles in Fig. 2.15.

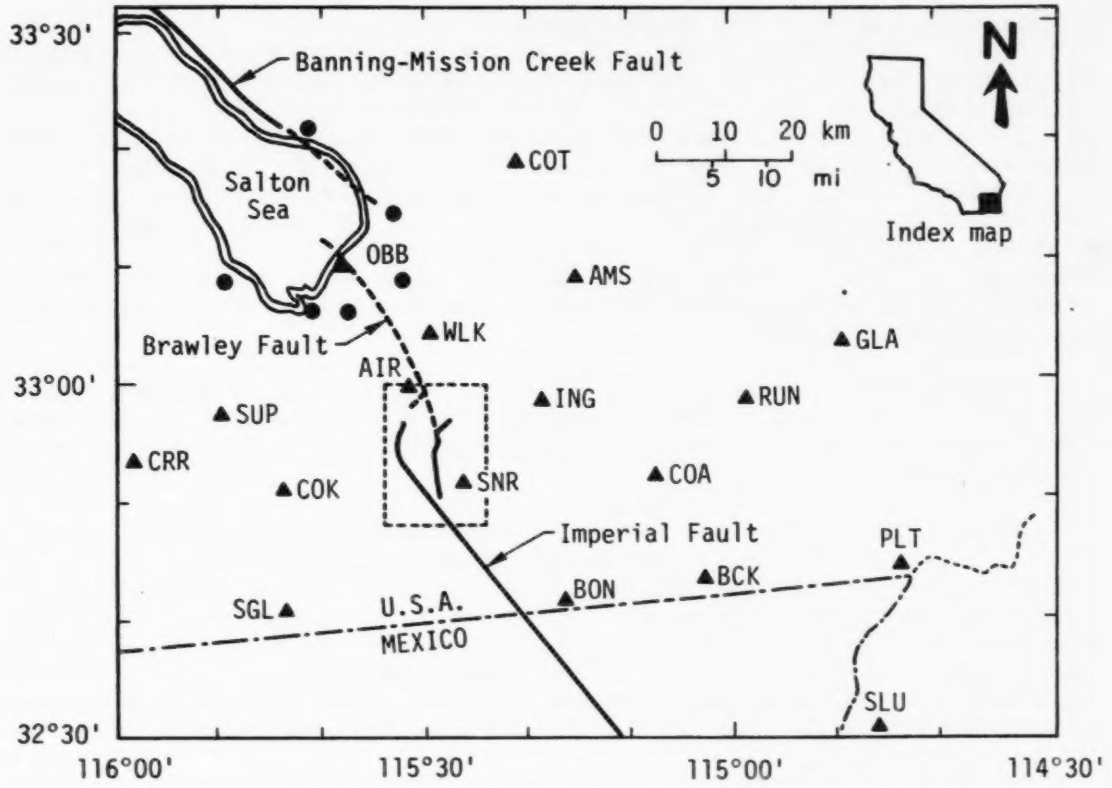
Chevron Oil Company has established a closely spaced seismic net in the Heber area to gather background baseline seismicity data and to detect potential seismicity induced by geothermal production.

Although not a microseismic monitoring network, an extensive array of 24 strong motion accelerograph stations has been established in Imperial Valley (Fig. 2.14). These stations will hopefuly provide additional information on many of the larger microseismic events. This dense array is operated jointly by USGS, the California Division of Mines and Geology, and Cal Tech to fulfill such specific research needs as source-mechanism and ground-motion attenuation studies (Porcella and Nielson, 1977).

A general discussion on seismic risk in Imperial Valley is presented in Geonomics (in press). This discussion concludes that once it has been established that a region, such as the Salton Trough, has had or will have large earthquakes, then ground condition and structural design at a specific site are as critical as the exact magnitude or location of an anticipated earthquake. So, although recurrence statistics show that Imperial Valley should experience a magnitude 7 earthquake about once every thousand years, and 12 earthquakes of magnitude 6 or greater have occurred since 1900, seismic risk must be evaluated on a detailed site and structure-specific basis.

2.4.2 Potential Induced Seismicity

A general discussion of the relationship between earthquakes and geothermal activity is presented in Geonomics (in press). This discussion notes that geothermal activity is often associated with naturally high seismicity levels, and that fluid withdrawal associated with geothermal production, with or without injection, may trigger local seismic activity.


33°30'
33°00'
32°30'
116°00'
115°30'
115°00'
114°30'
Banning-Mission Creek Fault
Salton Sea
Brawley Fault
Imperial Fault
U.S.A.
MEXICO
N
0 10 20 km
5 10 mi
Index map
COT
OBB
AMS
WLK
AIR
GLA
ING
RUN
SUP
CRR
COK
SNR
COA
PLT
BCK
BON
SGL
SLU

EXPLANATION

▲ USGS regional telemetered network, seismograph stations and identifying codes.

● ERDA/LLL seismograph stations added to USGS regional telemetered network in October, 1976.

(Three additional Cal Tech stations shown on Figure 2.12.)

⬚ Location of area shown in Fig. 2.13

Figure 2.15 Seismograph networks in Imperial Valley (Crow, 1976)

The currently producing geothermal field, The Geysers, in northern California, is associated with a much higher level of microseismicity than the surrounding area (Bufe, et al. 1976). However, the pre-production microseismicity rate is not known, so it cannot be determined if these earthquakes are a result of the geothermal production or of natural geothermal activity. It is anticipated that this after-the-fact lack of information will be avoided in Imperial Valley due to the extensive microseismic monitoring nets discussed in the previous subsection.

Although there are no empirical geothermal production-induced seismicity data currently available for Imperial Valley, Biehler and Lee (1977) discuss a theoretical evaluation of earthquake potential induced by geothermal energy extraction in Imperial Valley. This evaluation estimates that the seismicity rate will be 6.5 times the current historic rate for 1000 MWe power production and 2 times for a 100 MWe production. This estimate is based on many approximations and assumptions. The basis for the calculations is that extraction of fluid from a geothermal reservoir will induce volumetric contraction and thermal stress. Thermal contraction is used to calculate the seismic moment and the temperature change is coupled to the power production rate. The induced thermal stress will be added to the existing tectonic stress. Energy extraction can be related to thermally induced stress drops, which can thereby be related to magnitude. It is estimated that a 100 MWe plant will generate a 4.4 maximum magnitude earthquake per year, or if the stress were accumulated, one 5.4 maximum magnitude earthquake per 30 years.

Biehler and Lee (1977) further state that earthquakes may be induced by mechanisms other than the thermal contraction process which they describe, and that "induced seismic hazards are perhaps greater for higher rates of fluid injection or withdrawal than for low flow rates." It is recommended that the original report be consulted for the working details of the estimates.

2.5 SUBSIDENCE

Differential ground subsidence in Imperial Valley would have extremely significant environmental impact, particularly by disrupting the vast networks of gravity-flow irrigation canals which support the valley's agriculture and economy. Ground subsidence has been noted in other geothermal fields (Stilwell, et al. 1975) as well as in areas of oil, water or gas withdrawal and injection (Poland and Davis, 1969). Surface movement may also be caused by natural geologic processes, such as faulting, fault creep or other tectonic forces, induced hydraulic gradients, thermal changes or landslides; or by other agricultural or industrial processes; or by geothermal fluid withdrawal and/

or injection. A subsidence detection committee was formed in the Imperial Valley to study subsidence in connection with agricultural operations, but the county surveyor's office knew of no localized subsidence caused by agricultural operations.

Since Imperial Valley is one of the most tectonically active areas in the United States (Elders, et al. 1972), and does exhibit natural tectonic subsidence, one of the major objectives of a subsidence monitoring program in Imperial Valley will be to distinguish between ground movement caused by geologic processes and by geothermal power development. This will require years of baseline monitoring data collection and analysis. To this end, regional and local horizontal and vertical control networks, as well as tiltmeters and extensometers, have been installed in Imperial Valley to monitor pre-geothermal production baseline conditions, that is, naturally occurring horizontal and vertical ground movement. Periodic resurveys of these networks will provide data to calculate the changes that occur.

Much additional work has been done since Lofgren (1974) and Crow (1976) published papers describing the subsidence monitoring program in Imperial Valley. Although the program is basically the same as that described by Lofgren (1974), it has been considerably expanded. The existing network was releveled in the spring of 1977 and the data is currently being processed by the National Geodetic Survey in Rockville, Maryland. The USGS is planning to release an open file report in the fall of 1977 presenting the results of this current leveling survey, a discussion of the currently monitored horizontal and vertical control networks, the expansion of the networks since 1974, and planned expansion of the current program (B. Lofgren, 1977, pers. comm.). It is expected that this upcoming USGS open file report will considerably update the following discussion which is based largely on Lofgren (1974) and Crow (1976).

2.5.1 Baseline Data and Monitoring Programs

Triangulation and leveling data for the period 1934 to 1967 show complex horizontal motion and subsidence in Imperial Valley (Fig. 2.16). The northern and central parts of the valley show the greatest subsidence and the highest rate of downward movement has occurred around Brawley. The maximum subsidence of 1.5 to 3.0 cm (0.6 to 1.2 in.) may be related to the large number of recent earthquakes (Hill, et al. 1975), and the high strain rate on the Brawley and Imperial Faults (Elders, et al. 1972; Johnson and Hadley, 1976).

Chevron Oil Company has conducted a level survey in the Heber area which suggests a slight upward movement relative to El Centro, but the major portion of movement has been the more regional downward tilting northward and eastward, as discussed in the following section on vertical control networks.

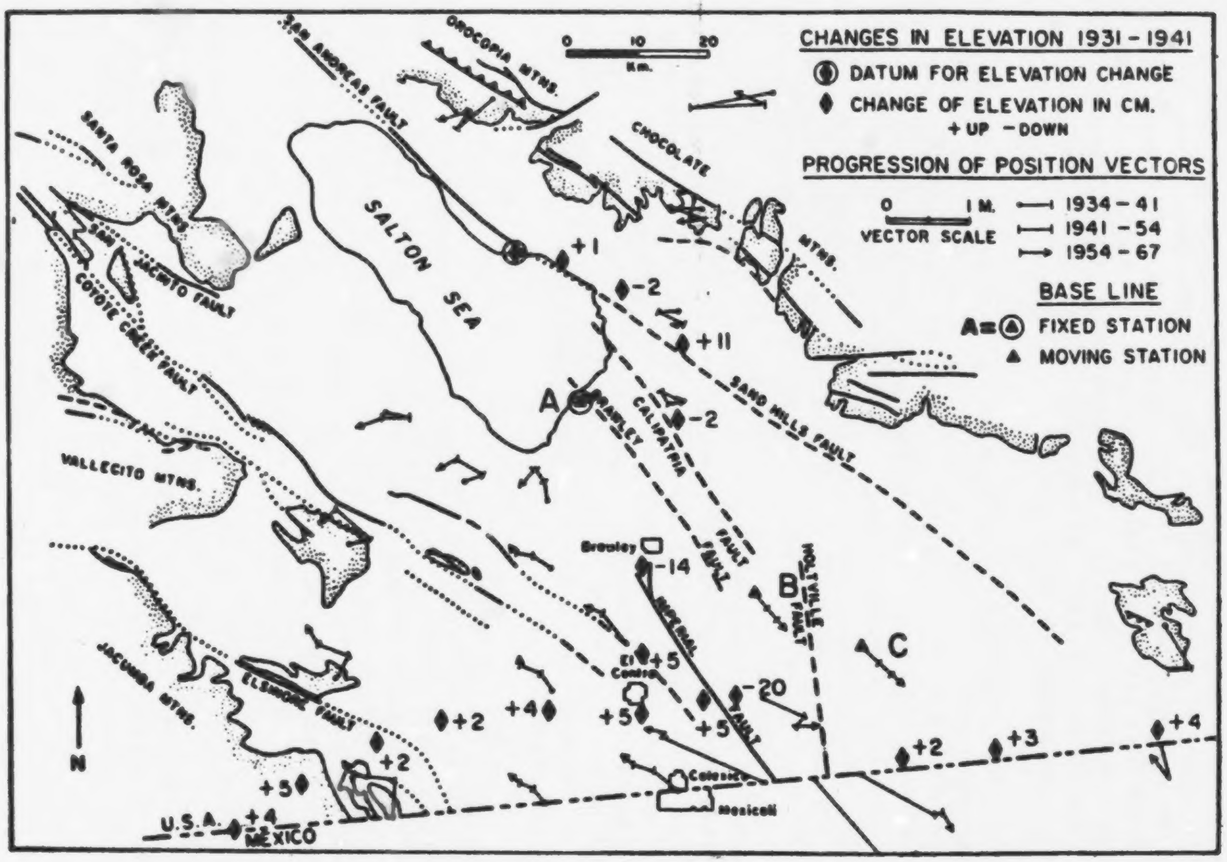

CHANGES IN ELEVATION 1931 - 1941
DATUM FOR ELEVATION CHANGE
CHANGE OF ELEVATION IN CM.
+ UP - DOWN
PROGRESSION OF POSITION VECTORS
0 1 M.
VECTOR SCALE
1934 - 41
1941 - 54
1954 - 67
BASE LINE
A = FIXED STATION
MOVING STATION
0 10 20
Km.
SAN ANDREAS FAULT
OROCOPIA MTNS.
CHOCOLATE
MTNS.
SANTA ROSA MTNS.
SAN JACINTO FAULT
COYOTE CREEK FAULT
SALTON SEA
VALLECITO MTNS.
JACUMBA MTNS.
ELSINORE FAULT
SAND HILLS FAULT
BRAWLEY
CALIPATRIA
FAULT
FAULT
Brawley
IMPERIAL
FAULT
HOLTVILLE FAULT
El Centro
Calexico
Mexicali
U.S.A.
MEXICO
A
B
C
N
+1
-2
+11
-2
-14
+5
-20
+5
+5
+4
+2
+2
+5
+4
+2
+3
+4

Figure 2.16 Geodetic measurement in the Imperial Valley from 1934 to 1967 (Elders, et al. 1972)

Presently, the USGS, the U.S. National Geodetic Survey, and the Imperial County surveyor are cooperating in the operation of the Imperial Valley subsidence monitoring networks. The Imperial Valley Environmental Project of LLL is conducting a survey of subsidence monitoring in Imperial Valley and is attempting to work with existing agency programs. They will establish second order leveling nets in the Salton Sea geothermal field area, the Coachella Canal northeast of the Salton Sea, the Brawley KGRA and the Heber geothermal field area, and will establish a horizontal control trilateration network in the Salton Sea geothermal area. (Crow, 1976). The proposed locations of the additional stations for the LLL second-order level net in the Salton Sea area are shown in Fig. 2.17.

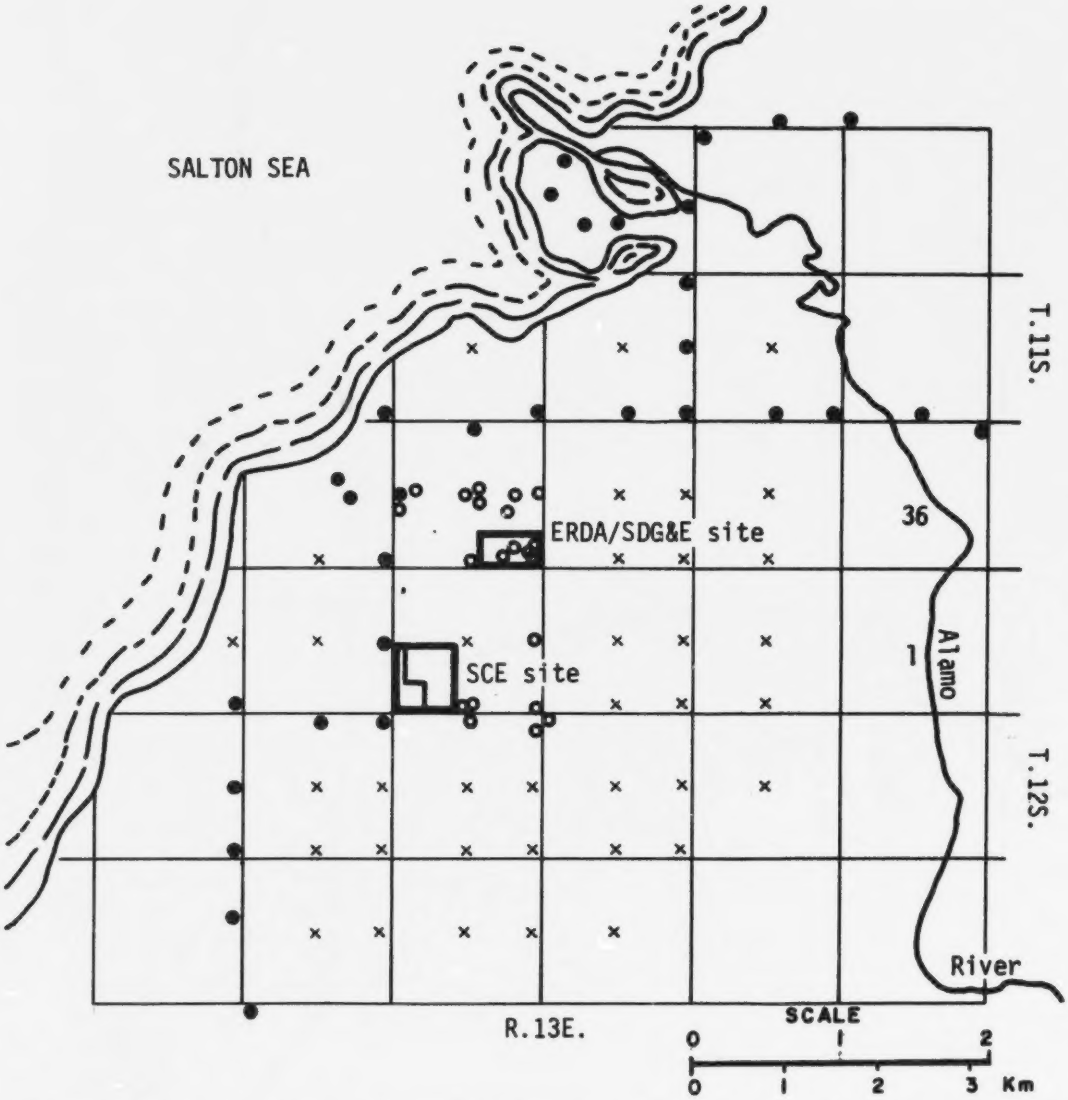
Existing subsidence monitoring networks are divided into three categories for the following discussion: 1) horizontal control networks, 2) vertical control networks, and 3) other measurement programs. Networks of both regional and local extent have been established. The vertical network consists of first- and second-order level lines, allowing maximum vertical errors, in mm, of 4.0 R_1 and 8.4 R_1 respectively, where R_1 is the distance surveyed, in kilometers. The regional horizontal network is capable of accuracies of 1 in 10^7 units, while the local networks are capable of accuracies of 2 in 10^6 units. The other measurement programs include sensitive local arrays of tiltmeters and extensometers. In addition, developers of geothermal wells are required by state and county ordinance to install several benchmarks near each well and to periodically resurvey and tie them into the first- or second-order level lines, in order to detect subsidence that may be related to geothermal production.

Vertical Control Network--

A regional network of first- and second-order leveling lines has been established in Imperial Valley (Fig. 2.18). There are north-south trending and east-west trending first-order level lines. The second-order lines are somewhat more ubiquitous and are distributed more irregularly throughout the valley. These lines have been surveyed several times prior to 1971, producing indications of significant tectonic movement.

The first-order lines (Fig. 2.18) were releveled in the winter of 1971-72 by the National Geodetic Survey and this survey was established as the reference datum. The second-order lines were established and tied into the first-order net by other agencies under the direction of the National Geodetic Survey.

A resurvey of the first- and second-order nets in 1973-74 showed the two-year change in elevations (Fig. 2.18). For this survey a bedrock tie west of El Centro was considered stable.


SALTON SEA
ERDA/SDG&E site
SCE site
36
1
Alamo
River
T.11S.
T.12S.
R.13E.
SCALE
0
1
2
0
1
2
3 Km

● Approximate location of Imperial County first- and second-order bench marks.
○ Approximate location of company second-order bench marks.
× Approximate location of additional ERDA/LLL second-order bench marks.

Figure 2.17 Local leveling network in Salton Sea geothermal field (Crow, 1976)

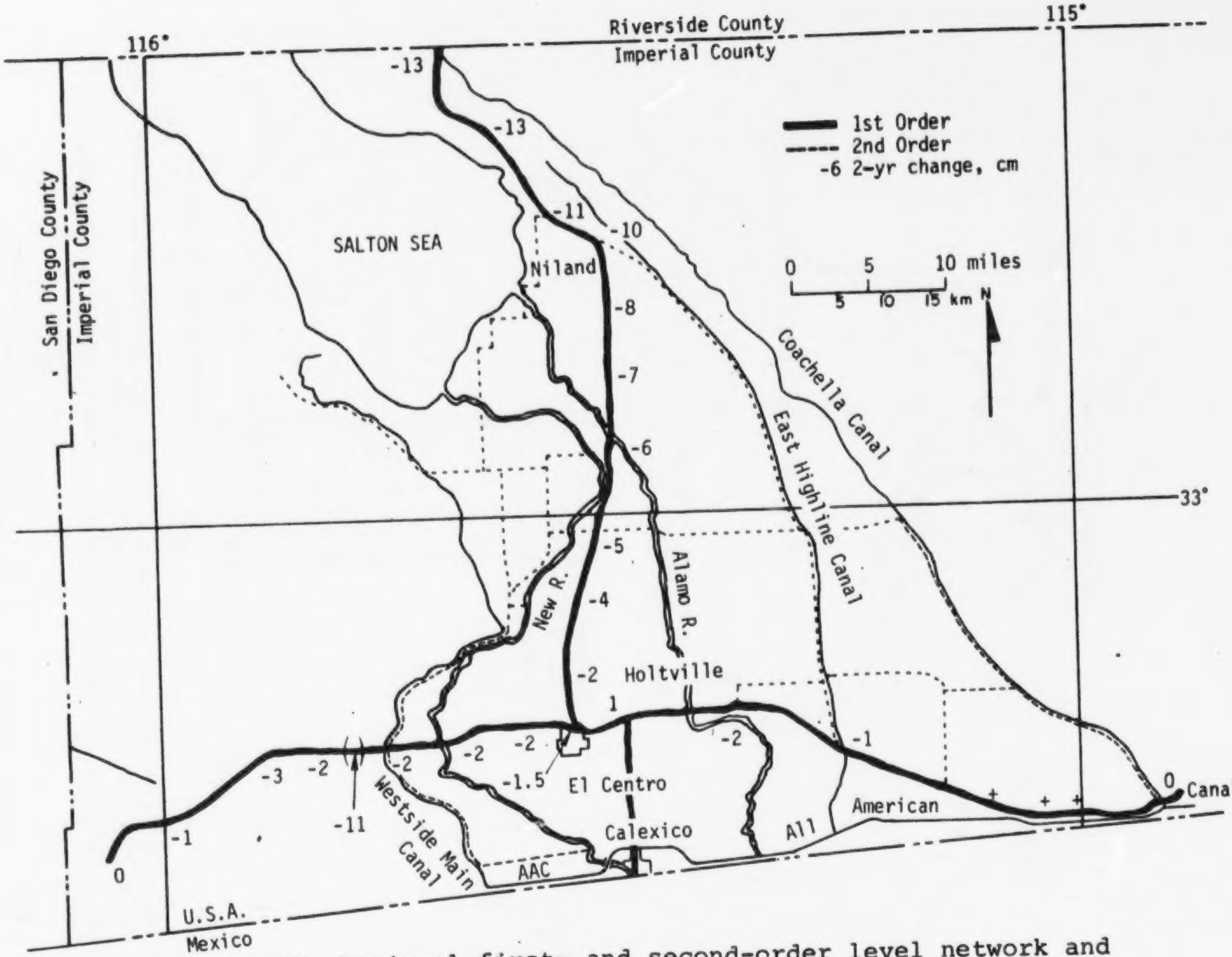

Riverside County
Imperial County
116°
115°
33°
San Diego County
Imperial County
1st Order
2nd Order
-6 2-yr change, cm
0
5
10 miles
5
10
15 km
N
SALTON SEA
Niland
Coachella Canal
East Highline Canal
Alamo R.
New R.
Holtville
El Centro
Calexico
Westside Main Canal
AAC
All
American
Canal
U.S.A.
Mexico
-13
-13
-11
-10
-8
-7
-6
-5
-4
-2
1
-2
-2
-1.5
-2
-2
-2
-2
-3
-11
-1
0
-1
0

Figure 2.18 Regional first- and second-order level network and vertical movement in Imperial Valley 1972-1974 (Lofgren, 1974, redrafted by Crow, 1976)

This vertical control data shows a definite northward-down tilting of 13 cm (5 in.) in the 85 km (53 mi) north-south length of the survey, with benchmarks near Calexico and the bedrock tie east of El Centro showing little or no change in this two-year period. The east-west pattern of elevation changes is not as distinct. They show the center of the valley dropping about 20 mm (0.79 in.) with respect to the mountains on the east and west margins.

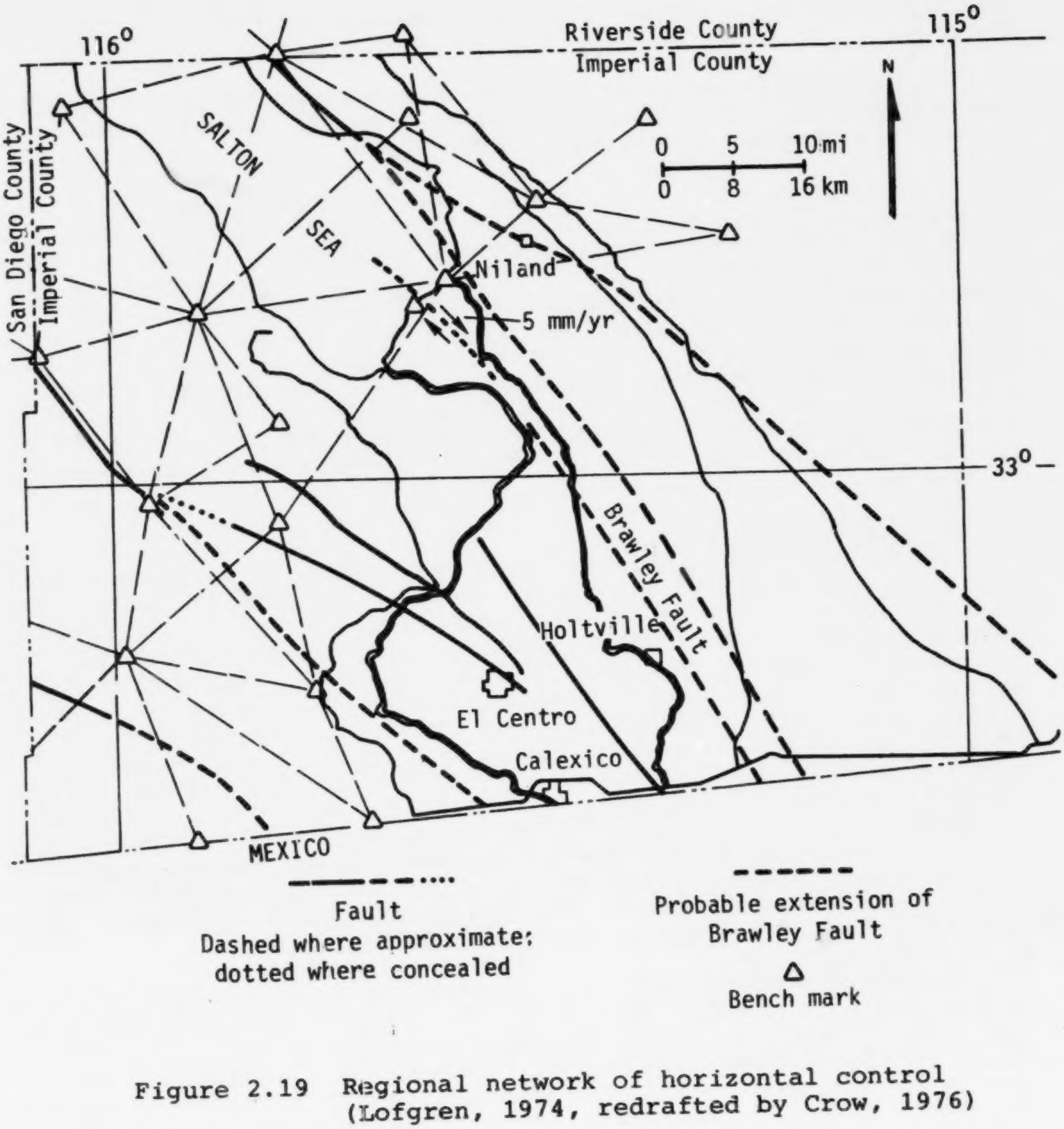
Local level networks are being monitored by developers in the Salton Sea, East Mesa and Heber areas to detect subsidence that may accompany geothermal production.

Two continuous (water level) stage recorders were installed at strategic locations near the southern shore of the Salton Sea to enable correlation of water-level fluctuations with two continuous stage recorders of long record on the western shore. These correlations may enable detection of elevation changes occurring on the southern margin of the Salton Sea, although they probably would not allow distinction between elevation changes due to tectonic readjustments or to geothermal development. Each of these stage gauges is tied into the valley-wide vertical control network and will be able to detect elevation changes of less than 1 cm (2.5 in.) around the southern margin of the sea.

Horizontal Control Network--

There are both regional and local horizontal control networks in Imperial Valley. The regional network of horizontal control (Fig. 2.19) is an extremely precise trilateration net consisting of 18 benchmarks spanning the valley. This net is intended to measure regional tectonic movement, while the local arrays of precise distance measurements at Salton Sea (Fig. 2.20), East Mesa (Fig. 2.21) and Heber are intended for detection of ground movement induced by geothermal development. However, the control lines in the local arrays do extend across structural zones where tectonic movement might occur. In fact, as much as 5 mm/yr (0.2 in.) of right lateral horizontal tectonic movement has been detected in the Obsidian Buttes area, on the southeast shore of the Salton Sea, along the Brawley Fault. Although a number of geothermal wells have been drilled in this area, the tectonic movement predates the drilling.

Distance measurements are being made at arrays in the Salton Sea (Fig. 2.20), East Mesa (Fig. 2.21) and Heber areas by the USGS. They can detect distance changes of only a few millimeters along these controlled lines using electronic distance measuring equipment. This is a relatively inexpensive technique and enables the collection of potentially useful extra measurements. This technique has been more successful at the Salton Sea area, where elevated reference points are available, enabling long line-of-sight controls, than at the flatter East Mesa and Heber areas.


116°
115°
Riverside County
Imperial County
San Diego County
Imperial County
N
0 5 10 mi
0 8 16 km
SALTON
SEA
Niland
5 mm/yr
33°
Brawley Fault
Holtville
El Centro
Calexico
MEXICO

Fault
Dashed where approximate:
dotted where concealed

Probable extension of
Brawley Fault

△
Bench mark

Figure 2.19 Regional network of horizontal control (Lofgren, 1974, redrafted by Crow, 1976)

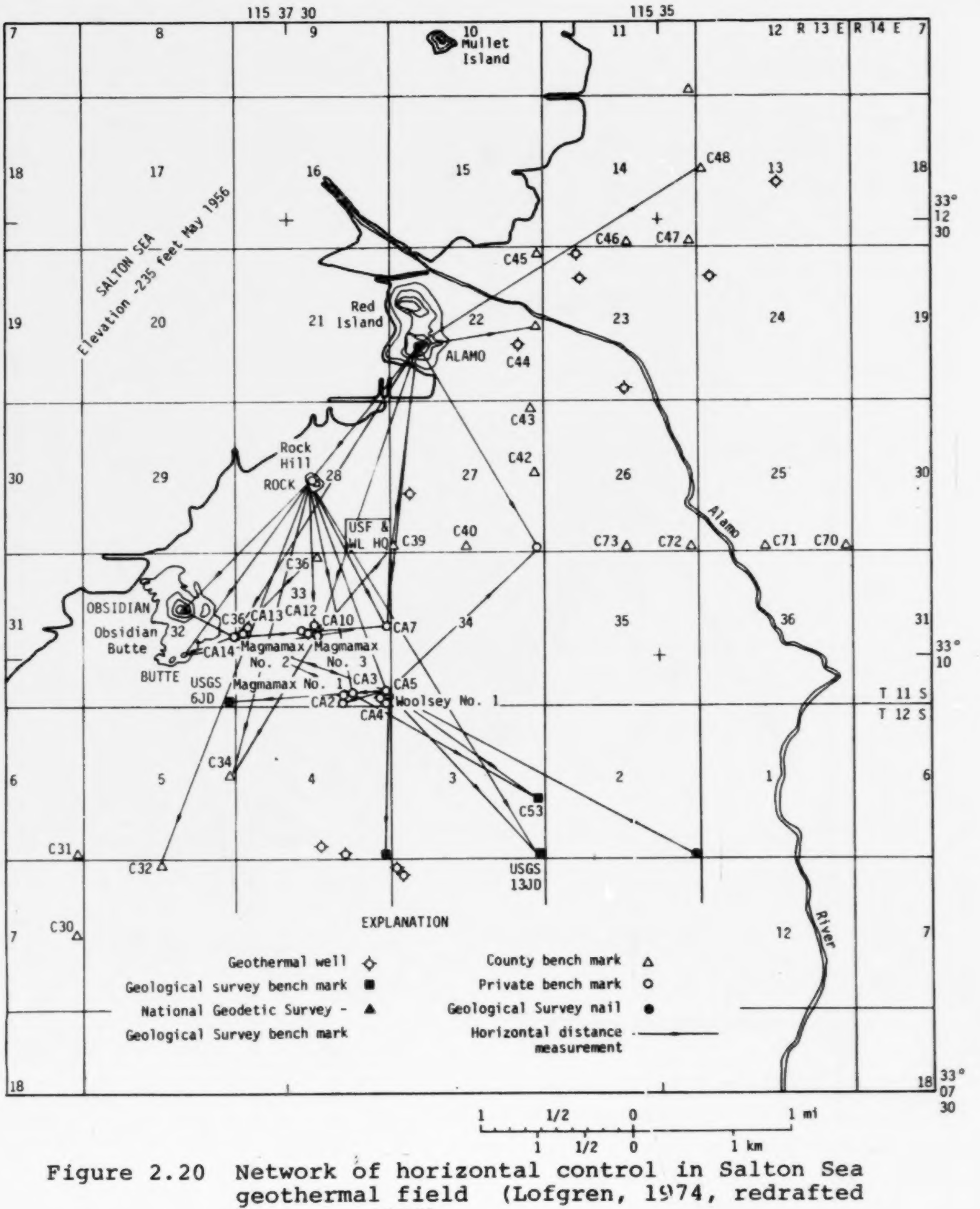

115 37 30
115 35
Mullet Island
R 13 E
R 14 E
33° 12 30
33° 10
33° 07 30
T 11 S
T 12 S
SALTON SEA
Elevation -235 feet May 1956
Red Island
ALAMO
Rock Hill
ROCK
OBSIDIAN
Obsidian Butte
BUTTE
USF & WL HQ
USGS 6JD
USGS 13JD
Magmamax No. 1
Magmamax No. 2
Magmamax No. 3
Woolsey No. 1
C30
C31
C32
C34
C36
C39
C40
C42
C43
C44
C45
C46
C47
C48
C53
C70
C71
C72
C73
CA2
CA3
CA4
CA5
CA7
CA10
CA12
CA13
CA14
Alamo River
EXPLANATION
Geothermal well ◇
Geological survey bench mark ■
National Geodetic Survey - Geological Survey bench mark ▲
County bench mark △
Private bench mark ○
Geological Survey nail ●
Horizontal distance measurement
1 1/2 0 1 mi
1 1/2 0 1 km

Figure 2.20 Network of horizontal control in Salton Sea geothermal field (Lofgren, 1974, redrafted by Crow, 1976)

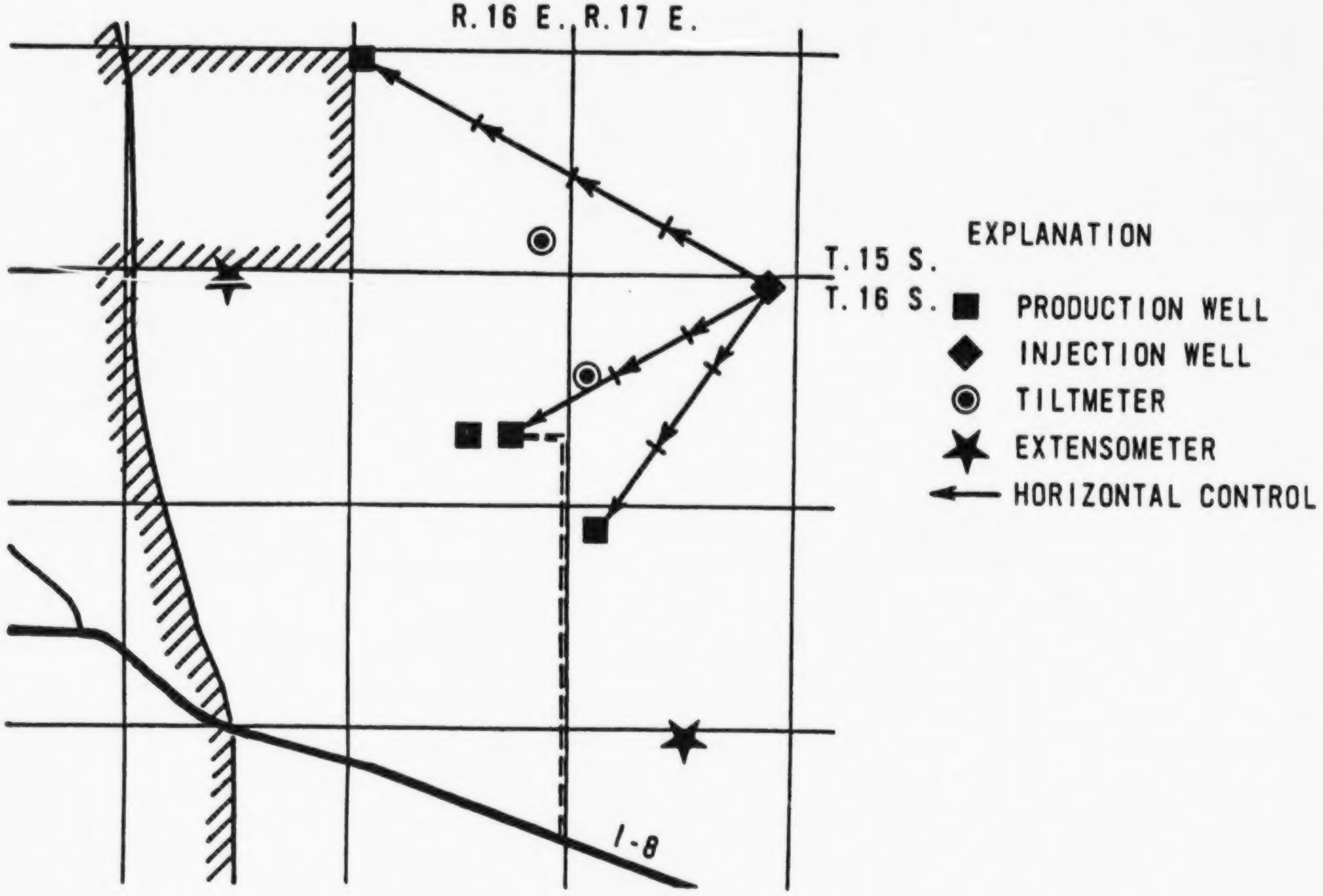

R. 16 E. R. 17 E.
T. 15 S.
T. 16 S.
EXPLANATION
■ PRODUCTION WELL
◆ INJECTION WELL
◎ TILTMETER
★ EXTENSOMETER
← HORIZONTAL CONTROL
I-8

Figure 2.21 Ground motion detection instrumentation installed at East Mesa geothermal area (Lofgren, 1974)

Other Measurement Programs--

Tiltmeters and extensometers have been installed in the East Mesa area (Fig. 2.21) to aid in defining precisely the mechanism of the ground motion associated with geothermal subsidence. This will aid in distinguishing between subsidence due to geothermal fluid withdrawal and injection and potential subsidence due to ground water pumping or other mechanisms. The extensometers are being installed in several locations where shallow groundwater is being pumped close to geothermal developments. Two mid-depth extensometers to monitor changes in water levels and compaction in the upper 350 and 430 m (1,150 and 1,400 ft), respectively, of alluvial deposits, are located between the geothermal development and nearby farmlands. These extensometers will help differentiate between deep compaction caused by geothermal production and shallow compaction due to shallow groundwater withdrawal. The tiltmeters will help determine whether the ground deforms as a stressed beam, develops vertical shear planes with geothermal subsidence, or perhaps deforms with some combination of the two mechanisms. Two sensitive tiltmeters installed at East Mesa (Fig. 2.21), in 3 m (10 ft) pits in order to minimize thermal interferences, are located between four production wells and one injection well.

2.5.2 Potential Subsidence

The degree of land subsidence resulting from geothermal development in Imperial Valley can only be conjectured at this time. Since it is anticipated that the spent geothermal fluid will be injected, subsidence due to brine production will probably be quite small, not larger than ground motion due to natural tectonism. However, since differential subsidence can wreak havoc with the gravity-flow irrigation canals, detailed analyses of this potential problem must be conducted prior to and during production.

Geonomics (1976a) provided a preliminary estimate of subsidence for geothermal development of the Heber reservoir. This report concludes that land surface elevation changes can be caused by changing reservoir fluid pressures, which are in turn affected by fluid withdrawal and injection. Studies conducted in the Wilmington Oil Field, Long Beach, California have successfully projected subsidence rates based on the relation between benchmark elevation changes, net fluid withdrawal and reservoir pressure differences. However, this technique requires data collected during actual production, and reliable estimates of future subsidence at Heber or other reservoirs cannot be made until such data are obtained.

The next best approximation of future subsidence may be made using computer models. However, it is a considerable problem to choose physical parameters that properly represent the reservoir. Many of these parameters, such as the elastic properties of the reservoir rock, distribution of in situ stresses, etc., are not known for the Imperial Valley geothermal reservoirs. However, preliminary results from a Chevron Oil Company computer model of the Heber reservoir suggest that subsidence due to production at Heber should pose no serious problem (Lloyd Mann, 1976, pers. comm.)

A rough estimate of possible subsidence at Heber, based on a method discussed by Geertsma (1973) and by Raghaven and Miller (1975), has been made by Geonomics (1976a). It should be noted that this is a very crude estimate and that the method does not account for temporal drawdown pressure variations or for any time lag in subsidence. The calculations were based on the following simplifying assumptions:

a) fluid production rate equals fluid injection rate

b) fixed overburden pressure

c) reservoir pressure drop of 6.8 to 20.4 atm (100 to 300 psia) around the well bores for a 200 MWe plant

d) average pressure drop for entire reservoir less than 6.8 atm (100 psia)

e) reservoir thickness of 734 m (2,408 ft)

f) a cylindrical disc shaped reservoir

g) Poissons' ratio of 0.2 for reservoir

h) the reservoir is isolated by an impermeable boundary

i) fluid withdrawal takes place from a circular array of wells; injection takes place through a concentric, outer, circular array of wells (S.K. Sanyal, 1977, pers. comm.)

The parameters used in the compaction and subsidence calculations are gross estimates and the assumed reservoir was idealized so the resulting "average" subsidence estimate of -0.21 m (-0.7 ft) during the estimated 30-year production life of Heber reservoir can only be considered as an "order-of-magnitude" estimate. It is believed that this is a conservative estimate and that the true "average" value will probably be less, but subsidence is expected to be greater around the producing wells.

2.6 POLLUTION CONTROL TECHNOLOGY

2.6.1 Current Practices

There are several geothermal injection wells in Imperial Valley for the purpose of waste disposal. Reinjection has been tested in several KGRAs in Imperial Valley which include Heber, East Mesa and Salton Sea. In Heber, successful reinjection for over one year has been recently carried out by Chevron Oil Company through Holtz No. 2 well. In East Mesa, well No. 5-1 has been used by USBR for injection of geothermal water during recent years. During 1964-1965, Union Oil Company carried out a successful reinjection test in the Salton Sea field. During the test period about 480 million liters (126 million gallons) of water were reinjected at the rate of 2,270 lpm (600 gpm). In all these cases reinjection was reasonably successful. However, considerable problems of scaling and corrosion of casing and pipes as well as plugging of reservoirs can be a serious problem in Imperial Valley, particularly in the Salton Sea and Brawley KGRAs where salinities are very high.

Ponding of geothermal wastes for temporary storage or evaporation has been successfully used in Imperial Valley. For example, in the 1960s, evaporation ponds were used for mineral extraction from geothermal waters in the Salton Sea area. To prevent contamination of groundwater at the East Mesa test facility prior to reinjection, waste brines are stored in a holding pond lined with a 0.254 mm (10 mil) PVC.

Electrohydraulics Corporation has installed a portable treatment facility for geothermal wastes in the East Mesa KGRA. Here wellhead geothermal water is subjected to a high voltage spark generated shock wave which reportedly precipitates soluble constituents; these constituents are removed by microstrainers (Chen, et al. 1976). Although Electrohydraulics Corporation claims that 80% to 90% of the soluble trace metals can be removed by this patented process, Chen, et al. (1976) could not make any definite conclusion as to the effectiveness of this treatment process. This company has a working agreement with Magma Electric, Inc. to evaluate their process.

For the past few years, USBR has been experimenting with a desalination facility for geothermal water at East Mesa. They have installed a multistage flash distillation unit and a vertical tube evaporator distillation unit in order to test and evaluate various procedures for desalting geothermal fluids. Product water having a TDS content of approximately 100 ppm can be obtained by this process. There have been scaling problems, with deposition of barium sulfate, strontium sulfate, calcium carbonate and silica in the tubes of the desalting units (USBR, 1977). The concentrated brine produced from the process is diverted to a holding pond where it undergoes evaporation. Presently, injection of this concentrate is being attempted.

REFERENCES

Allen, C. R., P. St. Amand, C. R. Richter and J. M. Nordquist. Relationship Between Seismicity and Geologic Structure in the Southern California Region. Bull. Seis. Soc. Am., v. 55, p. 753-787, 1965.

Anderson, D. N. and L. H. Axtell. Geothermal Resources in California; in Geothermal Overviews of the Western United States, Geothermal Resources Council, Davis, California, Special Report No. 1, 1972.

Babcock, E. A. Detection of Active Faulting Using Oblique Infrared Aerial Photography in the Imperial Valley, California; in Cooperative Geological-Geophysical-Geochemical Investigations of Geothermal Resources in the Imperial Valley Area of California, R. W. Rex, Principal Investigation, University of California, Riverside, p. 143-150, 1971.

Biehler, S. Gravity Studies in the Imperial Valley; in Cooperative Geological-Geophysical-Geochemical Investigations of Geothermal Resources in the Imperial Valley Area of California, R. W. Rex, Principal Investigator, University of California, Riverside, p. 19-43, 1971.

Biehler, S., R. L. Kovach and C. R. Allen. Geophysical Framework of Northern End of Gulf of California Structural Province; in Marine Geology of the Gulf of California A.A.P.G., Mem. 3, p. 116-143, 1964.

Biehler, S. and T. Lee. Final Report on Resource Assessment of the Imperial Valley. Dry Lands Research Institute Report No. 10, University of California, Riverside, 68 p., 1977.

Black, H. T. A Subsurface Study of the Mesa Geothermal Anomaly, Imperial Valley, California. University of Colorado Geothermal Energy Project, D. R. Kassoy, Project Director, 1975.

Black, W. E., J. S. Nelson and J. Combs. Thermal and Electrical Resistivity Investigations of the Dunes Geothermal Anomaly, Imperial Valley, California. EOS Trans. Am. Geophys. Un. 54, No. 11, p. 1214, 1973.

Brune, J. N. and C. R. Allen. A Microearthquake Survey of the San Andreas Fault System in Southern California. Bull. Seism. Soc. Am., v. 57, p. 277-296, 1967.

Bufe, C. G., J. H. Pfluke, F. W. Lester and S. M. Marks. Map showing Preliminary Hypocenters of Earthquakes in the Healdsburg Quadrangle, Lake Berryessa to Clear Lake, California. USGS Open File Report 76-802, 1976.

California Department of Water Resources. Geothermal Wastes and the Water Resources of the Salton Sea Area. Bull. No. 143-7, 123 p., 1970.

Chasteen, A. J. Geothermal Steam Condensate Reinjection; in Second United Nations Symposium on the Development and Use of Geothermal Resources, Proceedings, v. 2, p. 1335-1336, 1975.

Chen, J. Y., S. K. Gupta, W. Choi and B. Eichenberger. Chemistry, Fate and Removal of Trace Contaminants from Low to Medium Salinity Geothermal Waste Waters. National Science Foundation Report, November, 1976.

Combs, J. Heat Flow and Geothermal Resources for the Imperial Valley; in Cooperative Geological-Geophysical-Geochemical Investigations of Geothermal Resources in the Imperial Valley Area of California, R. W. Rex, Principal Investigator, University of California, Riverside, p. 5-28, 1971.

__________. Thermal Studies; in Cooperative Investigation of Geothermal Resources in the Imperial Valley Area and Their Potential Value of Desalting of Water and Other Purposes, R. W. Rex, Principal Investigator, University of California, Riverside, Section B, 1972.

Combs, J. and D. Hadley. Micro-earthquake Investigation of the Mesa Geothermal Anomaly, Imperial Valley, California. Geophysics, v. 42, No. 1, p. 17-33, 1977.

Coplen, T. B. Origin and the Geothermal Waters in the Imperial Valley of Southern California; in Cooperative Investigation of Geothermal Resources in the Imperial Valley Area and Their Potential Value for Desalting of Water and Other Purposes, R. W. Rex, Principal Investigator, University of California, Riverside, Section E, 1972.

__________. Cooperative Geochemical Resource Assessment of the Mesa Geothermal System. Institute of Geophysics and Planetary Physics, University of California, Riverside, Final Report to U. S. Dept. of the Interior, Bureau of Reclamation, Contract No. 14-06-300-2479, 97 p., 1976.

Coplen, T. B., J. Combs, W. A. Elders, R. W. Rex, G. Bruckhalter and R. Laird. Preliminary Findings of an Investigation of the Dunes Thermal Anomaly, Imperial Valley, California, and the Institute of Geophysics and Planetary Physics, University of California, Riverside, 1973.

Coplen, T. B. and P. Kolesar. Investigations of the Dunes Geothermal Anomaly, Imperial Valley, California: Geochemistry of Geothermal Fluids. Institute of Geophysics and Planetary Physics, University of California, Riverside, 20 p., 1974.

Cosner, S. and J. Apps. Lawrence Berkeley Laboratory Brine Data File. Revision February 3, 1977.

Crow, N. B. Subsidence and Seismicity; in Imperial Valley Environmental Project: Progress Report, P. L. Phelps and L. R. Anspaugh, Principal Investigators, Lawrence Livermore Laboratory, UCRL 50044-76-1, p., 83-100, 1976.

Dutcher, L. C., W. F. Hardt and W. R. Moyle, Jr. Preliminary Appraisal of Ground Water in Storage with Reference to Geothermal Resources in the Imperial Valley Area. USGS Circ. No. 649, 57 p., 1972.

Elders, W. A. and D. K. Bird. Petrological Studies; in Investigations of the Dunes Geothermal Anomaly, Imperial Valley, California, Institute of Geophysics and Planetary Physics, University of California, Riverside, No. 74-13, 14 p., 1974.

Elders, W. A., R. W. Rex, T. Meidav, P. T. Robinson and S. Biehler. Crustal Spreading in Southern California. Science, No. 178, p. 15-24, 1972.

Ermak, D. and M. Buchanan. Geothermal Resources; in A Description of Imperial Valley, California for the Assessment of Impacts of Geothermal Energy Development, D. Layton and D. Ermak, Principal Investigators, Lawrence Livermore Laboratory, UCRL 52121, p. 94-103, 1976.

Fernelius, W. A. Production of Fresh Water by Desalting Geothermal Brines - Pilot Desalting Program at the East Mesa Geothermal Field, Imperial Valley, California; in Second United National Symposium on the Development and Use of Geothermal Resources, Proceedings, v. 3, p. 2201-2208, 1975.

Garfunkel, Z. The Structure of the Salton Trough in Southern California; in Cooperative Investigation of Geothermal Resources in the Imperial Valley Area and Their Potential Value for Desalting of Water and Other Purposes, R. W. Rex. Principal Investigator, University of California, Riverside, Section I, 1972.

Geertsma, J. Land Subsidence Above Compacting Oil and Gas Reservoirs. J. Pet. Tech, June, 1973.

Geonomics, Inc. Geotechnical Aspects of the Environmental Impact of Geothermal Power Generation at Heber, Imperial Valley, California. Electric Power Research Institute, Res. Proj. 580, ER-299, Report No. 1, 79 p., 1976a.

_________. A Comparison of Hydrothermal Reservoirs of the Western United States. Electric Power Research Institute, Res. Proj. 580-1, ER-364, Topical Report No. 3, 170 p., 1976b.

_________. Baseline Geotechnical Data for Four Geothermal Areas in the United States. U.S. Environmental Protection Agency, Office of Research and Development, in press.

Hardt, W. F. and J. J. French. Selected Data on Water Wells, Geothermal Wells, and Oil Tests in Imperial Valley, California. USGS, Menlo Park, California, Open File Report, 1976.

Hegelson, H. C. Geologic and Thermodynamic Characteristics of the Salton Sea Geothermal System. Am. J. Sci., v. 266, p. 129-166, 1968.

Hileman, J. A., C. R. Allen and J. M. Nordquist. Seismicity of the Southern California Region, 1 January, 1932 to 31 December, 1972. Bull. Seism. Lab., California Institute of Technology, Pasadena, California, 1973.

Hill, D. P., P. Mowinckel and K. M. Lahr. Catalog of Earthquakes in the Imperial Valley, California, June 1973 to May 1974. USGS, Menlo Park, California, Open File Report No. 75-101, 25 p., 1975a.

Hill, D. P., P. Mowinckel and L. G. Peake. Earthquakes, Active Faults, and Geothermal Areas in the Imperial Valley, California. Science, v. 188, p. 1306-1308, 1975b.

Hinrichs, T. C. and H. W. Falk, Jr. The East Mesa "Magamax Process" Power Generation Plant; in Geothermal: State of the Art, Geothermal Resources Council, Transactions, v. 1, p. 141-142, 1977.

Irelan, B. Salinity of Surface Water in the Lower Colorado River Salton Sea Area. USGS Prof. Paper 486-E, 39 p., 1971.

Jacobson, W. O. Recent Operational Experience at the SDG&E/ERDA Niland Geothermal Loop Experimental Facility; in Geothermal: State of the Art, Geothermal Resources Council, Transaction, v. 1, p. 153-156, 1977.

Jennings, C. W. Geological Map of California, Salton Sea Sheet. Calif. Div. Min. Geol., 1976.

_________. Fault Map of California. Calif. Div. Min. Geol., California Geology Data Map Series, Map No. 1, Faults, Volcanoes, Thermal Springs, and Wells, 1975.

Johnson, C. E. and D. M. Hadley. Tectonic Implications of the Brawley Earthquake Swarm, Imperial Valley, California. Bull. Seis. Soc. Am. v. 66, No. 4, p. 1133-1144, 1976.

Kovach. R. L., C. R. Allen and F. Press. Geophysical Investigations in the Colorado Delta Region. J. Geophys. Res., v. 67, p. 2847-2871, 1962.

Layton, D. and D. Ermak. A Description of Imperial Valley, California for the Assessment of Impacts and Geothermal Energy Development. Lawrence Livermore Laboratory, UCRL 52121, 53 p., 1976.

Littleton, R. I. and E. Brunett. Chemical Profile of the East Mesa Geothermal Field Imperial County, California; in Second Workshop on Sampling and Analysis of Geothermal Effluents, February 15-17, 1977, Las Vegas, Nevada, U. S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, in press.

Loeltz, O. J., B. Irelan, J. H. Robinson and F. H. Olmstead. Geologic Reconnaissance of the Imperial Valley, California. USGS Prof. Paper 486-K, 1975.

Lofgren, B. E. Measuring Ground Movement in Geothermal Areas of Imperial Valley, California. Conference on Research for the Development of Geothermal Energy Resources, Pasadena, California, Proceedings, p. 128-133, 1974.

Mathias, K. E. The Mesa Geothermal Field - A Preliminary Evaluation of Five Geothermal Wells; in Second United Nations Symposium on the Development and Use of Geothermal Resources Proceedings, v. 3, p. 1741-1747, 1975.

Meidav, T. Resistivity Studies of the Imperial Valley Geothermal Area, California. Geothermics, v. 1, No. 2, p. 47-62, 1972.

Meidav, T. and R. W. Rex. Investigation of Geothermal Resources in the Imperial Valley and Their Potential Value for Desalination of Water and Electricity Production. University of California, Riverside, 54 p., 1970.

Meidav, T. and R. Furgerson. Resistivity Studies of the Imperial Valley Geothermal Area, California. Geothermics, v. 1, No. 2, 1972.

Meidav, T., R. James and S. Sanyal. Utilization of Gravimetric Data for Estimation of Hydrothermal Reservoir Characteristics in the East Mesa Field, Imperial Valley, California. Stanford Geothermal Program Workshop on Geothermal Reservoir Engineering and Well Simulation, Stanford University, 1975.

Meidav, T., R. West, A. Katzenstein and Y. Rotstein. An Electrical Survey of the Salton Sea Geothermal Field, Imperial Valley, California. Lawrence Livermore Laboratory Project No. 8432305, 1976.

Muffler, L. J. P. and B. R. Doe. Composition and Mean Age of Detritus of the Colorado River Delta in the Salton Trough, Southeastern California. J. of Sed. Petrol., v. 35, p. 384-399, 1968.

Muffler, L. J. P. and D. E. White. Active Metamorphism of Upper Cenozoic Sediments in the Salton Sea Geothermal Field and Salton Trough, Southeastern California. Bull. Geol. Soc. Am. v. 80, p. 157-182, 1969.

Nathenson, M. and L. J. P. Muffler. Geothermal Resources in Hydrothermal Convection Systems and Conduction - Dominated Areas; in Assessment of Geothermal Resources of the United States - 1975, D. E. Williams and D. L. Williams, ed., USGS Circ. 726, p. 104-121, 1975.

Nugent, J. M. and L. R. Vick. Well Operations Salton Sea Geothermal Field; in Geothermal: State of the Art, Geothermal Resources Council, Transactions, v. 1, p. 233-234, 1977.

O'Connell, M. F. and R. F. Kaufmann. Radioactivity Associated with Geothermal Waters in the Western United States. U. S. Environmental Protection Agency, Office of Radiation Programs, Las Vegas Facility, Las Vegas, Nevada, Technical Note ORP/LV 75-8A, 25 p., 1976.

Palmer, T. D. Characteristics of Geothermal Wells Located in the Salton Sea Geothermal Field, Imperial County, California. Lawrence Livermore Laboratory, UCRL-51976, 54 p., 1975.

Palmer, T. D., J. H. Howard and D. P. Lande. Geothermal Development of the Salton Trough, California and Mexico. Lawrence Livermore Laboratory UCRL-51775, 1975.

Phelps, P. L. and L. R. Anspaugh. Imperial Valley Environmental Project: Progress Report. Lawrence Livermore Laboratory, UCRL-50044-76-1, 214 p., 1976.

Poland, J. F. and G. H. Davis. Land subsidence due to Withdrawal of Fluids; in Reviews in Engineering Geology, v. 2, p. 187-269, 1969.

Porcella, R. L. and J. D. Nielson. Preliminary Report on the Calipatria, California, Earthquake Swarm: November, 1976; in Seismic Engineering Program Report, October-December, 1976, R. L. Procella, ed., USGS Circ. 736-D, p. 1-3, 1977.

Raghavan, R. and F. G. Miller. Mathematical Analysis of Sand Compaction; in Compaction of Coarse-Grained Sediments I, G. V. Chillingarian and K. H. Wolf, eds., Developments in Sedimentology 18A, p. 403-524, 1975.

Randall, W. Percent Volume Sand Bodies in the Imperial Valley: Preliminary Report; in Cooperative Geological-Geophysical-Geochemical Investigations of Geothermal Resources in the Imperial Valley Area of California, R. W. Rex, Principal Investigator, University of California, Riverside, p. 119-124, 1971.

__________. An Analysis of the Subsurface Structure and Stratigraphy of the Salton Sea Geothermal Anomaly, Imperial Valley, California. University of California, Riverside, Ph.D. Dissertation, December 1974.

Renner, J. L., D. E. White and D. L. Williams. Hydrothermal Convection Systems; in Assessment of Geothermal Resources of the United States - 1975, D. E. White and D. L. Williams, eds., USGS Circ. 726, p. 5-57, 1975.

Reed, M. J. Chemistry of Thermal Water in Selected Geothermal Areas of California. Calif. Div. Oil and Gas, Report No. TR15, 1975.

Rex, R. W. Investigations of Geothermal Resources in the Imperial Valley and Their Potential Use for Desalination of Water and Electricity Production. University of California, Riverside, 14 p., 1970.

Rex, R. W., E. A. Babcock, S. Biehler, J. Combs, W. A. Elders, R. B. Furgerson, Z. Garfunkel, T. Meidav, P. T. Robinson. Cooperative Investigations of Geothermal Resources in the Imperial Valley Area of California, 1971.

Rex, R. W., S. Biehler, J. Combs, T. B. Coplen, R. B. Furgerson, Z. Garfunkel, T. R. Getts, J. P. Maas and M. Reed. Cooperative Investigations of Geothermal Resources in the Imperial Valley Area and Their Potential Value for Desalting of Water and Other Purposes. University of California, Riverside, 1972.

Richter, C. F. Elementary Seismology. W. H. Freeman and Company, Inc., 1958.

Shannon, D. W. Economic Impact of Corrosion and Scaling Problems in Geothermal Energy Systems. Battelle Pacific Northwest Laboratories for the U. S. Atomic Energy Commission, 115 p., 1975.

Sharp, R. V. Surface Faulting in Imperial Valley During the Earthquake Swarm of January-February, 1975. Bull. Seism. Soc. Am., v. 66, No. 4, p. 1145-1154, 1976.

Stilwell, W. B., W. K. Hall and J. Tashai. Ground Movement in New Zealand Geothermal Fields; in Second United Nations Symposium on the Development and Use of Geothermal Resources, Proceedings, v. 2, p. 1427-1434, 1975.

Towse, D. An Estimate of the Geothermal Energy Resource in the Salton Trough, California. Lawrence Livermore Laboratory, UCRL-51851, 22 p., 1975.

U.S. Public Health Service. Public Health Service Drinking Water Standards, PHS pub. 956. U. S. Govt. Printing Office, 1962.

U.S. Bureau of Reclamation, Geothermal Resource Investigations, Imperial Valley, California, A Status Report. U. S. Dept. of the Interior, 47 p., 1971.

U.S. Bureau of Reclamation. Geothermal Resource Investigations, East Mesa Test Site, Imperial Valley, California, A Status Report. U. S. Dept. of the Interior, 1974.

U.S. Bureau of Reclamation. Geothermal Resource Investigations, East Mesa Test Site, Imperial Valley, California, Status Report. U. S. Dept. of the Interior, 99 p., 1977.

Witherspoon, P. A., T. N. Narasimhan and D. G. McEdwards. Results of Interference Tests from Two Geothermal Reservoirs. Soc. of Pet. Engineers of AIME, Paper No. 6052, 10 p., 1976.

SECTION THREE

THE GEYSERS

3.1 INTRODUCTION

3.1.1 Summary

Field development at The Geysers is continuing with at least 41.5 sq km (16 sq mi) of productive reservoir proven, 502 MW electricity currently being generated, and 400 MW electric generating capacity under construction. Steam, with less than 1% average of noncondensible gases, is produced from wells averaging 2,130 m (7,000 ft) in depth. Excess condensate is reinjected into the deep reservoir under hydrostatic head. However, approximately 80% of the condensate is evaporated into the atmosphere during the cooling process in the cooling towers of the 11 operating power plants. The steam contains an average of 222 ppm hydrogen sulfide and abundant carbon dioxide, with hydrogen sulfide emissions exceeding air quality standards.

Cool regional groundwaters contain abundant calcium, magnesium and bicarbonate, abundant boron and carbon dioxide, and sparse chloride or sulfate. Thermal waters of a wide region are enriched in boron, hydrogen sulfide, carbon dioxide and sometimes chloride. These appear to be derived from interaction of hot water with Franciscan Formation and other rocks. The heat source is a suspected magma at several miles in depth. No magmatic constituents are recognized.

The region is seismically active. However, no induced seismicity is recognized as a result of steam production or reinjection activities. Similarly, no ground subsidence is recognized.

Work is underway to reduce hydrogen sulfide emissions to meet state and local standards. Stringent control over water discharges essentially prevents geothermal fluid from entering surface or shallow groundwaters.

3.1.2 Background

Data for this study come from several sources. These include Water Supply Papers prepared by the USGS for several water basins (but not including The Geysers); geological mapping by geologists from federal, state, university and private organizations; and published articles from symposia volumes, short-course curricula, field trip guidebooks and environmental impact statements. These data deal with aspects of reservoir management, steam well characteristics, fluid composition, status of field development, and existing or hypothesized operating problems. Other data come from unpublished reports and files, and deal with chemical compositions, field development schedules and well performance.

There are significant gaps in the data. Very little is available from any source on possible freshwater aquifers within the geothermal field. Almost nothing exists on chemistry of local groundwaters at The Geysers, other than for the original fumaroles and boiling springs. So little is available on long-term productivity of the geothermal field, especially on the deeper sections, that this is a topic of intense argument. Many specific questions remain unanswered, such as the lateral and vertical distribution of noncondensible gases within the field, or the possible variation with time of gas concentration in wellhead fluid.

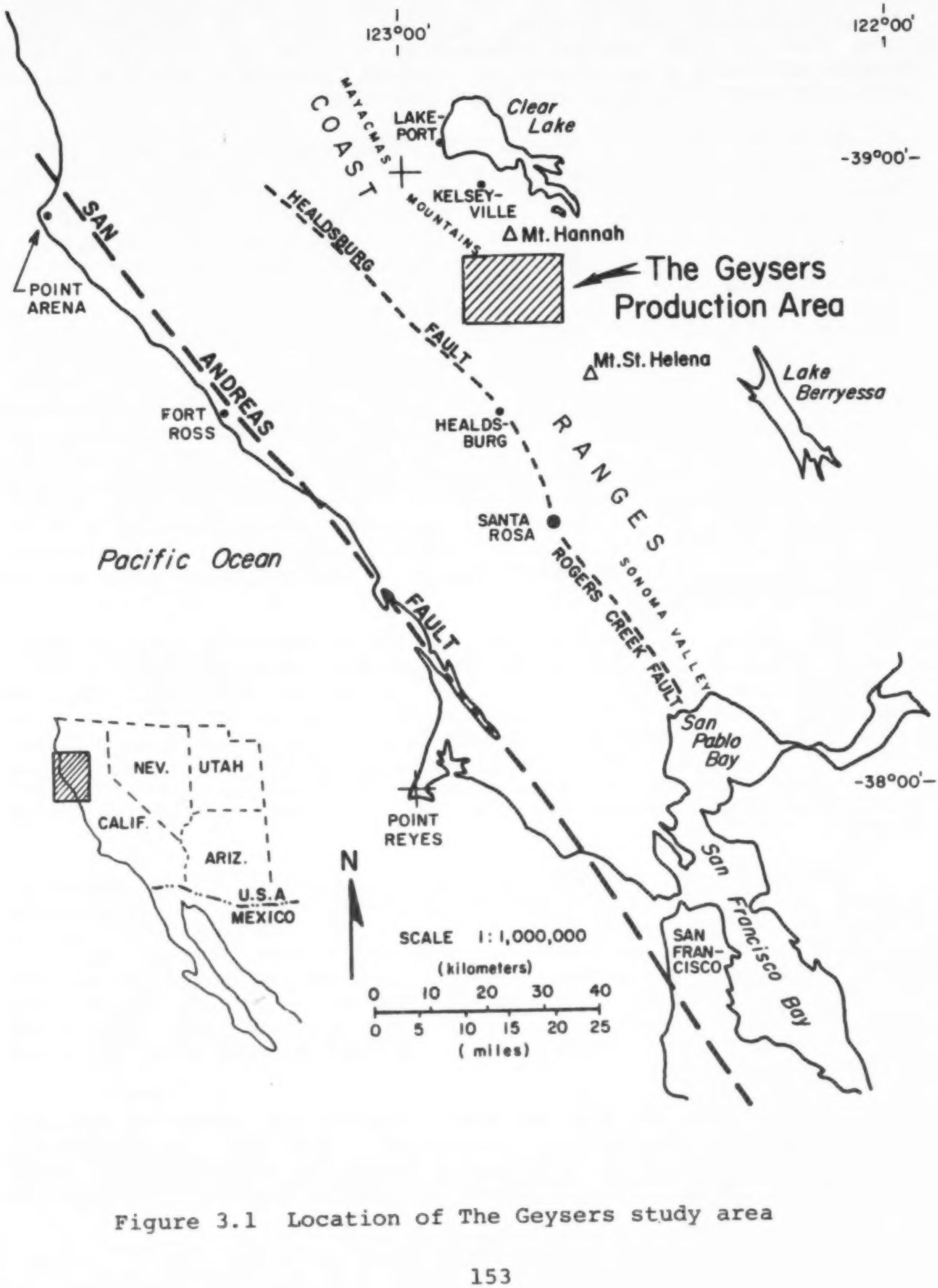
Meteorological monitoring has been underway for some time by Pacific Gas and Electric Company (PG&E), Stanford Research Institute and others. Results to date appear not to have general significance.

Although many unanswered questions, incomplete analyses and hypothesized situations remain, there currently is sufficient data available to define many aspects of pollution potential. Data from current and future projects and investigations will answer many questions and clarify many of the presently ambiguous situations.

3.2 GEOTHERMAL SYSTEM

3.2.1 Definition of System

The Geysers geothermal field is located about 130 km (80 mi) due north of San Francisco, in the Mayacmas Mountains of the California Coast Ranges, in Sonoma and Lake Counties (Fig. 3.1). The field extends across at least 41 sq km (16 sq mi), and may exceed 52 sq km (20 sq mi) in area. The actual extent is unknown and is problematic. Certain relatively cool and/or hot but low yield wells at the west, northwest, northeast and southeast margins of production may represent field boundaries. However, occasional holes within the field have been nonproductive. This complicates any attempt to quantify resource extent.


123°00'
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MAYACMAS MOUNTAINS
COAST
RANGES
LAKE-PORT
Clear Lake
KELSEY-VILLE
Δ Mt. Hannah
The Geysers Production Area
HEALDSBURG FAULT
SAN ANDREAS FAULT
POINT ARENA
Mt. St. Helena
Lake Berryessa
FORT ROSS
HEALDS-BURG
SANTA ROSA
Pacific Ocean
ROGERS CREEK FAULT
SONOMA VALLEY
San Pablo Bay
NEV.
UTAH
CALIF.
ARIZ.
U.S.A
MEXICO
POINT REYES
N
SCALE 1:1,000,000
(kilometers)
0 10 20 30 40
0 5 10 15 20 25
(miles)
San Francisco Bay
SAN FRAN-CISCO

Figure 3.1 Location of The Geysers study area

It is known that the geothermal fluid comes to within several tens of meters of the surface at Big Sulphur Creek, where fumaroles and boiling springs issued in earlier days. This part of the system apparently is fed by leakage from a deeper and much more widespread system, upward along the northwest-southeast trending Sulphur Creek Fault.

Original drill holes in the 1920s encountered dry, superheated steam at depths of 60 to 150 m (200 to 500 ft) along this fault, in or adjacent to fumarole banks. The steam flowed at about 14 to 18 kg/sq cm (200 to 250 psig), 5 kg/sec (40,000 lb/hr), and with 2.8° to 16.7°C (37° to 62°F) of superheat. Wells drilled in the late 1950s entered this same part of the system, at depths that reached 300 m (1,000 ft) or slightly greater. Superheat in these shallow holes gave rise to the often-quoted statement that The Geysers is a superheated system.

Continued drilling encountered a deeper, stronger, higher pressure system, whose fluid is dry steam at about the maximum enthalpy for saturated conditions. Specifically, temperatures are about 232° to 243°C (450° to 470°F), shut-in pressures commonly range from 32 to 35 kg/sq cm (450 to 500 psig), flows initially average 19 to 25 kg/sec (150,000 to 200,000 lb/hr) from a 22.2 cm (8 3/4 in) hole, and enthalpy usually is 2.79 to 2.82 x 10^6 J/kg (1,338 to 1,350 BTU/lb). Pressure and enthalpy values are clouded somewhat because of the presence of about 1% of noncondensible gases.

The deeper system has been first encountered from as shallow as 610 m (2,000 ft) along Big Sulphur Creek to over 2,300 m (7,500 ft) in outpost wells to the northeast and west. Maximum depth of steam occurrence is over 2,600 m (8,500 ft), with no indication that permeability had been restricted or eliminated below that depth. Absolute elevation of the producing deeper steam reservoir varies between sea level and -2,000 m (-6,600 ft). The depth given is that of the commercially producing horizon.

Therefore, in calculating resource extent, it is common to assume an average of about 1,520 m (5,000 ft) of producible formation. This calculation yields a minimum reservoir volume of some 67 cu km (16 cu mi). Few wells are drilled to over 2,600 m (8,500 ft) because friction-limited maximum flow usually is achieved at shallower depth. However, certain wells have been redrilled or deepened to increase flow at some time after initial completion. Precise data is held confidential by field operators.

Calculations of the resource usually are based on the net kilowattage of electricity generated. That is, approximately 9 kg (20 lb) of steam produce 1 kW.hr of electricity. Well yield declines with time, as either local depletion occurs or wells are damaged by scaling, corrosion or other factors. Therefore, despite initial productivity that may reach 38 kg/sec (300,000 lb/hr) of steam, average sustainable production is about 19 kg/sec (150,000 lb/hr). This yields about 7,500 kW (7.5 MW) per well of continuous electric generation.

Well spacing is an arguable point. Initially, no thought was given to spacing and possible interference, with the result that wells were located as close as 61 m (200 ft) apart (0.8 ha [2 acre] spacing). These wells interfered badly, and were depleted rapidly. Today, 16-ha (40-acre) spacing is accepted generally or 6 per sq km (16 per sq mi), with opportunity for drilling make-up wells at 8-ha (20-acre) centers or 12 per sq km (32 per sq mi) over an assumed 30-year plant life.

Budd (1973) published performance curves suggesting nonlinear but rapid declines in steam flow at 2-ha (5-acre) spacing, such that a 50% decline might be expected within 6 years of production. However, for 8-ha (20-acre) spacing this was less than 30% decline; and for 18-ha (45-acre) spacing, decline was about 18%. Further, these decline rates were leveling off.

Therefore, using 7.5 MW per well, 16-ha (40-acre) spacing, and a minimum of 41 sq km (16 sq mi) of proven field, a production of almost 2,000 MW electricity is predicted for a plant life of 30 or more years. Reed and Campbell (1975) suggested 5,000 MW from an area of 1,000 sq km (400 sq mi) as the ultimate developable capacity. This figure appears high, and cannot easily be supported.

Natural recharge into the field is debatable. Probably some flow of water takes place into the field. This has been estimated from 1 or 2% of withdrawal per unit area to perhaps 10 to 15%. It is supplemented by reinjection of some 18 to 20% of blowdown from the plant cooling tower (condensed steam). Therefore, total natural and induced recharge probably does not exceed one-third of production under most favorable conditions.

Formation porosity is estimated by several methods to be 5 to 10%, distributed irregularly as fractures. Allowing for the greater specific heat of water, some 80 to 90% of the heat content of the system is in the rock, with only 10 to 20% in the fluid. Therefore, even recharge of up to one-third of the fluid mass should withdraw only 3 to 7% additional of the total heat. This assumes conductive heat recharge to be negligible.

However, because the distribution of fractures is irregular, the effect of recharge may be to deplete heat locally from the rock. This might cause fluid enthalpy to drop to the point where liquid water would locally dominate vapor in the rock.

Probably there is liquid water in coexistence with steam in the formation; this is indicated by the enthalpy values. The source of this water may be 1) recharge, or 2) convection within the formation from greater depth. The latter presupposes existence of a water table at some great but unknown depth, as suggested by several workers.

Chemically, the fluid produced is over 99% pure steam (Finney, 1973). The nature and concentration ranges of noncondensible gases are given in Table 3.1 (Allen and McCluer, 1975; Finney, 1973).

TABLE 3.1 NONCONDENSIBLE GASES IN STEAM SUPPLIED TO TURBINES AT THE GEYSERS

	Range, % by Weight				
Gas	Low	High	Average of 61 Wells	Average ppm, of Total Flow	Plant Design (volume % of Total Flow
Carbon dioxide(CO_2)	0.029	3.06	0.326	3,260	0.79
Hydrogen sulfide(H_2S)	0.0005	0.160	0.0222	222	0.05
Methane(Ch_4)	0.0013	0.1447	0.0194	194	0.05
Ammonia(NH_3)	0.00094	0.106	0.0194	194	0.07
Nitrogen(N_2)	0.0006	0.0638	0.0052	52	0.03
Hydrogen (H_2)	0.0011	0.0218	0.0056	56	0.01
Ethane (C_2H_6)	0.0003	0.0019	0.0008	8	-
TOTAL	0.120	3.41	0.398	3,986	1.00

Additionally, trace amounts of xenon, radon, argon, arsenic, mercury and a volatile compound of boron are known or suspected to be present in the steam (Reed and Campbell, 1975).

The distribution of these gases within the reservoir formation is unknown. In certain wells, there is evidence that noncondensible gases are concentrated in the upper part of the column, and that fluid quality in these wells improves with time as the noncondensibles are depleted. This is arguable.

Steam discoveries have been made by companies or groups of companies operating jointly: Magma Power Company-Thermal Power Company-Union Oil Company; Aminoil USA, Inc. (successor in interest to Signal Oil Company and Burmah Oil and Gas Company); Thermogenics Inc. (successor in interest to Pacific Energy Corporation and Geothermal Resources International, Inc.); Shell Oil Company; Geothermal Kinetics, Inc.; and McCulloch Oil Corporation. PG&E is the only consumer to date; however, the Northern California Power Association (NCPA) has negotiated purchase of steam from Shell Oil Company.

Exploratory drilling will continue on the northeastern, northwestern, western and southeastern boundaries of the known field according to permit applications on file with various agencies. Drilling will be done by the companies listed above and by Chevron Oil Company, AMAX Exploration, Inc., Sun Oil Company, Republic Geothermal, Inc., and possibly others.

The effect of this planned work may be to expand known field boundaries.

In any event, in-field development drilling may be expected to continue for the indefinite future, to meet the anticipated development schedule for PG&E. Some 502 MW of power plant capacity are in operation presently; over 400 more are approved for construction, and may be on line by 1980. Applications for additional plant sites can be anticipated from PG&E and NCPA.

All production to date is of steam with little or no water content. This steam is scrubbed free of rock particles and passed through condensing turbines, barometric condensers and cooling towers. Evaporative cooling releases some 80% of the fluid to the atmosphere as water vapor. The remainder of the water, as noted above, is reinjected as excess condensate.

With increasing production, reinjection, and development beyond the presently known field boundary, wet steam or even hot water may be produced, at least locally. This may require additional separation prior to use, or even development of a hot water or binary cycle system. It is unknown what changes in nature and concentration of noncondensible gases will be found with time, distance from the center of the field or with continued reinjection.

The Geysers region is believed to be active seismically, as is much of northern California. Continued or accelerated production from the geothermal field may have an effect upon seismicity and seismic risk. This is discussed in section 3.4 below. Ground subsidence is not believed to represent a problem in this area of metamorphosed sedimentary and igneous rock (see section 3.5 below).

The potential for renewed volcanism has been discussed by Hearn, Donnelly and Goff (1975). If geothermal production is achieved closer than at present to the very youthful eruptive centers around Clear Lake (Mount Konocti and other places), approximately 20 km to the north, there is an extremely remote possibility that an unpredictable future volcanic eruption would involve the geothermal system in some way as to cause increased discharge of pollutants from production facilities. This is considered highly improbable.

3.2.2 Potential Pollutants

Pollutants, or potential pollutants, from The Geysers geothermal system fall into five major categories: pollutants to the atmosphere; pollutants to ground or surface waters; noise pollution; aesthetic or visual degradation; degradation of the land surface.

Atmospheric pollution, noise, aesthetic considerations and land use factors are beyond the scope of this study, so, although it is realized that the current major environmental problems at The Geysers are due to air and noise pollution, the major emphasis of this section is on water pollution potential.

Potential pollutants from steam at The Geysers are reported in Table 3.2. Argon and xenon were reported by various sources, but were not quantified in any satisfactory manner. All of the pollutants listed in Table 3.2 may be volatilized and liberated into the atmosphere. However, it is most likely that all of these will be present in the steam condensate, concentrated by evaporation of water in the cooling process, along with varying amounts of ammonia or its oxidation products, nitrate and carbon dioxide.

TABLE 3.2 POTENTIAL POLLUTANTS REPORTED FROM STEAM AT THE GEYSERS

Pollutant	Concentration, Unit	Measurement Point	References
Radon (Rn)	8.3 picocuries/l	Steam sample from well	Reed & Campbell (1975)
Boron (B)	0.01 ppm	well Thermal #7	Anderson (1975)
	5.0 ppm	well DX-State 3395-1	Anderson (1975)
	0.02 ppm	well Sulfur	Anderson (1975)

(continued)

TABLE 3.2 (continued)

Pollutant	Concentration, Unit	Measurement Point	References
Boric Acid (HBO_2)	12-223 ppm	Ranges of values, wells	Reed & Campbell (1975)
Arsenic (As)	0.002-0.05 ppm	Range of values, wells	Reed & Campbell (1975)
Mercury (Hg)	0.00031-0.018 ppm	Range of values, wells	Reed & Campbell (1975)

There is great uncertainty in the range of values reported for these pollutants. This may reflect stratification, or regional enrichment in these gases in certain (unspecified) parts of the reservoir. However, these figures suggest the following daily production of pollutants in 1980 when 907 MW (net) are expected to be on line (Table 3.3).

TABLE 3.3 EXPECTED DAILY PRODUCTION OF SELECTED POLLUTANTS FROM 907 MW (NET), ANTICIPATED IN 1980

Constituent	Range, Unit/Day	
Mercury (Hg)	2.27 - 133 gm	(0.08 - 4.7 oz)
Arsenic (As)	15.0 - 371 gm	(0.53 - 13.1 oz)
Boric Acid (HBO_2)	89.5 - 1,661 kg	(197 - 3,655 lb)

As described previously, these pollutants are likely to be produced from an area of about 23 sq km (9 sq mi) (2,330 ha [5,760 acres]), and to be brought in with steam to some 15 central collection points (power plants). If one or more were to discharge to the surface, significant pollution could occur. However, all condensate water is reinjected and none has been discharged to surface drainage since 1971.

Steam condensate is evaporated in cooling towers, so that nearly 80% is evaporated to the atmosphere. Little of the boric acid, and very little of the mercury and arsenic, is evaporated; hence, concentrations in the condensate taken for reinjection are nearly four times those given in Table 3.2. Obviously, protection of surface and subsurface waters against contamination by the reinjectant becomes an important goal.

Other sources of possible pollutants come from the drilling, road building and plant construction processes. This includes silt and dust raised by stripping of vegetation and by movement of cars and trucks; cement wastes from construction; rock cuttings from drilling operations; paper, plastic and metal wastes from construction; human wastes; fuels and lubricants spilled accidentally; and drilling muds and additives. Of these, only drilling muds can be discussed in any quantitative terms.

Reed and Campbell (1975) reported a typical drilling mud composition, as given by Union Oil Company. This appears as Table 3.4 below.

TABLE 3.4 TYPICAL DRILLING MUD COMPOSITION, THE GEYSERS

Component	Composition	Volume %
Water	H_2O	93.09
Bentonite	$Na_{0.33}Al_{2.67}Si_{3.67}O_{20}(OH)_2$	5.93
Quebracho (Wood extract)	Organic	0.45
Caustic soda	NaOH	0.32
Sodium Bicarbonate	$NaHCO_3$	0.09
Lignin (Tannathin)	$C_{212}H_{171}O_{41}H_3S$	0.12
Additional Material Used to Control Lost Circulation		
Cottonseed hulls	Organic	
Walnut shells	Organic	
Mica	$K\ Al_3Si_3O_{10}(OH)_2$	

Reed and Campbell (1975) also reported that approximately 240 cu m (8,000 cu ft) of drilling fluid are used in an average well. Some of this enters the formation and is not recovered. The remainder may be stored in a specially constructed clay-lined sump or in a steel tank, partially evaporated, and then transported to a disposal site. Nontoxic mud wastes may be evaporated to dryness and used as fill in an area protected from erosion. Toxic (or suspected toxic) wastes must be hauled to a Class 1 Disposal Site.

Despite rumors of heavy metals as selected additives in drilling muds, only the relatively inert mineral barite can be documented at The Geysers, and then only rarely is it used.

Of all the pollutants described in this section, hydrogen sulfide presents the greatest potential problem. If emitted to the atmosphere without control, emissions can reach levels exceeding the local Air Pollution Control District (APCD) regulations in settled areas, since air patterns may carry it east, to Cobb and Collayomi Valleys.

PG&E has installed experimental scrubbing units on individual plants which, if used successfully on a permanent basis, could reduce hydrogen sulfide emissions to less than 2.7 metric tons (3 tons) per day. This would be almost one-eighth of the present loading; but even at this reduced level it obviously will permit further degradation of air quality. Additional hydrogen sulfide may be emitted during testing of individual wells (from 24 hours to 24 days) or during accidental well blowout. No control has been designed for these situtions.

3.3 WATER POLLUTION POTENTIAL

3.3.1 Summary of Baseline Water Characteristics

Very little is available on water quality or local and regional aquifers in The Geysers geothermal field. Elsewhere, as in Big Valley on the southwest side of Clear Lake, or in the Collayomi Valley, east of The Geysers (Upson and Kunkel, 1955), data have been compiled and evaluated. For a discussion of this, see Geonomics (in press).

Generally, water wells are confined to alluvium, which rarely is deeper than a few meters, except in Big Valley. Few wells penetrate bedrock. Therefore, almost all chemical and flow data pertain to surface streams and/or unconfined aquifers.

Very fragmentary published and unpublished analyses show ground water and surface streams and springs to be dominated by calcium and sodium bicarbonate. Locally, especially in the vicinity of serpentinite bodies, water contains higher magnesium than sodium and occasionally even than calcium values. This is not surprising, as serpentinite is hydrous magnesium silicate, and breaks down readily under surface weathering.

Chloride concentration varies appreciably, but does not appear to exceed a few tens of ppm in cool ground or surface waters. Most analyses report between 1 and 7 ppm of chloride. Sulfate, where data are available, is similar in concentration. Certain thermal waters northeast of The Geysers field have high chloride concentrations, reaching a maximum several thousand ppm of chloride at Wilbur Springs. However, that area is far beyond the scope of this report.

TDS range from a few dozen ppm in bedrock springs to perhaps over 1,000 ppm in deeper waters of Big Valley. This is based on several partial analyses and measurements of specific conductance.

There is a significant regional boron anomaly in cool and thermal groundwaters across the Mayacmas Mountains of Lake, Sonoma and Napa Counties. This extends from north of Clear Lake to south of Calistoga, a distance of over 65 km (40 mi). Levels of boron reach 7 ppm in Big Valley in cool groundwater (California Department of Water Resources, 1957), and reportedly reach over 100 ppm in selected thermal waters. For example, the thermal springs and shallow wells at Calistoga have several tens of ppm of boron, and at Sulphur Bank on the northeast side of Clear Lake boron have exceeded 100 ppm in certain incomplete analyses.

A major anomaly in ammonia, reaching several hundred ppm, is recognized at Clear Lake in thermal waters (Roberson and Whitehead, 1961), and may extend into thermal areas to the south.

Fumaroles at The Geysers have discharged copious quantities of hydrogen sulfide, ammonia, boric acid and carbon dioxide for centuries. Significant local anomalies existed at the surface before geothermal development began. Obviously, names like Big Sulphur Creek and Sulphur Bank reflected actual conditions. It is impossible to quantify these discharges with any certainty, as most fumaroles have ceased to discharge.

Other thermal springs of the region discharged one or more of the following: carbon dioxide, chloride, ammonia, boric acid,. hydrogen sulfide. Carbon dioxide seeps are widespread along shores of Clear Lake and in major stream canyons. Extinct hydrogen sulfide seeps are marked by sulfur deposits at several places.

In summary, cool surface and unconfined groundwaters are dominated by calcium and bicarbonate, with abundant magnesium and sodium, occasional boron and minor chloride and sulfate. TDS is low (1,000 ppm maximum). Carbon dioxide seeps are common. Thermal waters are sodium bicarbonate, with subsidiary calcium, magnesium and locally abundant chloride and sulfate. Boron, ammonia, carbon dioxide and hydrogen sulfide may be abundant. Certain thermal waters contain great quantities of these constituents. Fumaroles of The Geysers are dominated by hydrogen sulfide, ammonia and carbon dioxide, with significant boron.

3.3.2 Potential Water Pollutants

As described above, pollutants within The Geysers area are anticipated to be boron (or some compound of boron), ammonia and hydrogen sulfide. Chloride is a possible pollutant in areas outside The Geysers. Arsenic, mercury and radon are in low concentrations. Carbon dioxide will evolve from many surface and groundwaters.

3.3.3 Potential Pollution Mechanisms and Pathways

It is believed that all pollutants derive from attack of thermal waters on country rock. Possibly some carbon dioxide, ammonia, boron and sulfur derive from the magma believed to underlie the region at depth; but there are no isotope data to support this possibility. However, attack by hot water is a convincing mechanism, and a magmatic source is not needed.

Mixing of thermal and cool surficial waters can account for reduced levels of boron, carbon dioxide, ammonia and sulfur compounds noted in many areas. Chloride is derived from a suite of Mesozoic age rocks believed to have residual quantities of connate water. Chloride is relatively rare in Franciscan rocks of The Geysers area.

Therefore, it is quite reasonable to suppose that these pollutants circulate through fractured bedrock in thermal waters, and that all groundwaters in the region might contain quantities of any or all of these substances. The nearly total absence of wells drilled into Franciscan bedrock, other than at The Geysers, makes it difficult to test this hypothesis. When thermal water rises from fractured bedrock into the relatively thin alluvium, it may issue as mineralized springs or it may mix with cool surficial or unconfined groundwater, thereby diluting these pollutants. Regional anomalies of pollutants are suspected.

3.3.4 Level of Potential Pollution

All fluid produced from geothermal wells is either a) evaporated to the atmosphere, or b) reinjected into deep wells in the geothermal field. Therefore, no additional pollution of surface or groundwaters is expected from routine geothermal operations. If there are abnormal conditions (accidents, earthquakes, etc.), pollutants may be discharged onto the surface. As described earlier, the pollutants include boron, hydrogen sulfide (which will volatilize to over 85%), ammonia (largely volatilized), and very minor quantities of other substances.

Discharges of drilling muds (see section 3.2.1) may add trace amounts of other substances to surface waters (Table 3.5).

The relative impermeability of Franciscan rock at the surface tends to preclude significant recharge of pollutants to the groundwater regime. In any event, these pollutants issued from the subsurface in that area, and their return to depth could not be considered detrimental.

3.4 SEISMICITY

A study of seismicity of The Geysers must include seismic activity across a wider area of northern California, to determine the location of faults that might have seismic effects on operations at The Geysers and to determine relative seismic hazards.

3.4.1 Summary of Baseline Seismicity and Seismic Risk

Baseline data come from the USGS (National Center for Earthquake Research [NCER]); the University of California, Berkeley (U.C.B.), Seismograph Station; and the California Division of Mines and Geology. These include seismic records, microseismic surveys, strong-motion accelerograph records, compilations of epicenters, compilations of historical seismicity, projections of maximum acceleration, maximum magnitude and maximum intensity to be encountered, and maps of active or Quaternary faults.

The lack of population in the Mayacmas Mountains relative to the adjoining alluviated valleys makes it difficult to evaluate historical reports of earthquakes. Do fewer reports mean fewer events or fewer persons to report events? This question is discussed below.

Earthquake hazards consist of two distinct classes of ground movement: vibrational and permanent. The degree of these hazards varies geographically as a function of seismic potential and near-surface geologic conditions. Seismic risk (the probability of property loss or human injury) is a function of both the naturally occurring seismic hazards and the earthquake resistance of manmade works. Where there are no manmade structures, seismic risk is vanishingly small. Prediction of seismic risk means prediction of all of the following: the location, magnitude and frequency of earthquakes; vibratory motion in rock; the response of unconsolidated earth materials to these rock motions; and the response of manmade structures to resultant ground-surface motions.

Hazard elements to be discussed are: a) seismic potential (earthquake location, magnitude and frequency of occurrence); b) vibratory rock and ground motion; and c) permanent ground motions including faulting, liquefication, landsliding, differential settlement and lurch-cracking.

Since 1855, more than 140 earthquakes have been felt in the Santa Rosa-Sonoma Valley-Clear Lake region. While some ten of these did significant damage in Santa Rosa and Sonoma Valleys, only one was destructive in The Geysers region itself. This was the great 1906 (M = 8¼) earthquake, caused by rupture along the San Andreas Fault. Modified Mercalli (MM) intensity ranged from about VII to IX in the Santa Rosa Valley, reaching IX in the city of Santa Rosa due to soft, saturated ground conditions there. In the Mayacmas Mountains, MM intensity was about VI to VII, with very minor damage reported from The Geysers. Around Clear Lake, damage was confined to alluviated areas along the north and west shores: MM intensity VII prevailed in the area from Kelseyville to Upper Lake, as evidenced by fallen chimneys; fissures were reported in alluvial ground south of Kelseyville. Damage to any given type of structure in The Geysers-Clear Lake region was controlled by shallow ground conditions, being minimal on bedrock and maximal on water-saturated unconsolidated alluvium.

Other than the 1906 event, no shock in the region has been of sufficient magnitude to cause significant damage in The Geysers area. The largest had a magnitude estimated to have been near 5, and produced intensity VII (fallen chimneys) at Upper Lake and along the Russian River from Healdsburg to Ukiah; these places are located beyond the margins of The Geysers geothermal area, and on alluvium. Maximum MM intensity within The Geysers area probably did not exceed VI on alluvium and V on bedrock for any of these other shocks.

In 1969 two earthquakes with magnitudes 5.6 and 5.7 occurred on the southern end of the Healdsburg Fault on the north side of Santa Rosa. They caused substantial damage to buildings in Santa Rosa, but not within The Geysers area.

Frequency of occurrence of strong ground shaking (intensities VI, VII and VIII) has been nearly as great in Santa Rosa Valley as in the entire San Francisco Bay region. For The Geysers area, data are more sparse, reflecting thinner settlement. Probably, however, recurrence of strong shaking is lower than at Santa Rosa. This reflects a) greater distance from major active faults, and b) shallow bedrock.

If the last 160 years are fairly representative of long-term seismicity of the Bay region, we should expect potentially damaging ground shaking (intensity VII or greater) about once every 30 years on the average in alluviated portions of the region. On bedrock within The Geysers region, the "30-year intensity" is probably about VI; intensity VII or greater may be expected about once every century; and intensity VIII or more, which may be damaging to modern structures, about once in three centuries. However, the seismic record is short relative to long-term variations of regional crustal strain, and instrumental magnitudes are available only since 1932.

The greater San Francisco Bay region, extending from Monterey Bay on the south to Ukiah on the north and east to Vacaville, is one of the most seismically active areas of California. Seismicity was much higher in this region during the nineteenth century than it has been in the twentieth: since the great 1906 earthquake a few moderate (magnitude less than 6.0) and no major shocks have occurred; however, between 1836 and 1906 there were five major (magnitude probably greater than 7.0), and a number of moderate shocks.

Table 3.5 shows that for the period 1932 to 1971 seismicity (per unit area) of the Santa Rosa 1° by 2° Sheet is similar to that of the larger central Coast Range zone for magnitudes 6 and greater. Therefore, the long-term unit area seismicity of the two regions should be similar. From this, it is concluded that the recurrence intervals for the central Coast Range for 1810-1931 are a reasonably good indicator of future seismicity affecting the study region. Geodetic and geologic data suggest a recurrence interval of from 100 to 400 years for magnitude 8 or greater earthquakes at any place along the San Andreas Fault. This is in satisfactory agreement with the seismicity data.

Earthquake epicenter maps have been compiled by U.C.B. and the USGS. The accuracy of U.C.B. epicenters in this area is probably better than ±5 km (3 mi) for magnitude 3½ or greater shocks; however, before 1963, when the U.C.B. seismography network was greatly improved, accuracy probably improved from about ±20 km (12 mi) in 1910 to ±10 km (6 mi) in 1962. For this reason, one cannot see distinct clustering of epicenters along any active faults.

Immediately following the Santa Rosa earthquakes in 1969, NCER of USGS extended its dense Bay Area seismograph network into the Santa Rosa Valley area. This yielded a better correlation between epicenters and the mapped traces of the Rodgers Creek-Healdsburg Fault Systems (Fig. 3.1). This correlation appears because of the relatively high accuracy and precision of the NCER data: epicenters are accurate to better than ±2 km (1.2 mi).

Both the USGS and U.C.B. data indicate a lack of seismicity along the San Andreas Fault; this is characteristic of the fault northward from the Santa Cruz Mountains to Point Arena. Crustal strain apparently is still low there, but geodetic measurements at Fort Ross and Point Reyes indicate that strain is now accumulating along the San Andreas Fault.

The NCER data show high microseismicity in The Geysers geothermal field, but epicenter locations do not resolve specific active faults. It seems safe to say that seismicity there is produced by microfracturing throughout the geothermal field. This probably is the result of low-level strain release which is

TABLE 3.5 EARTHQUAKE RECURRENCE INTERVALS FOR THE CENTRAL COST RANGE

Earthquake Data Set			Recurrence Parameters*		Average Recurrence Intervals (yrs)				
					1,000 km^2		12,000 km^2		
Region	Area (km^2)	Period (years)	a	b	†M: 6	7	6	7	8
Santa Rosa Sheet	12,000	1944-1971	1.42	0.72	720	3600	60	300	1500
Central Coast Ranges	33,000	1932-1961	2.83	0.90	370	2960	32	250	2000
Central Coast Ranges	37,000	1810-1931	0.84	0.53	216	735	18	62	210

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*Parameters of the equation $\log N = a-b\,M$;
'a' is normalized on an annual and per 1000 km^2 basis.

†magnitude

localized by high temperature and pore pressure in the geothermal system. To the east in the Clear Lake area, microseismicity is much lower than in The Geysers area. Nearly one half of all microearthquakes in this area occurred in a two-day-long swarm located under the south flank of Mount Konocti and 1.6 km (1 mi) west of the trace of the Konocti Bay Fault. As all of these shocks had a similar focal mechanism with modal plans paralleling the fault, the shocks may have occurred on that fault. Therefore, it is concluded that the Konocti Bay Fault is seismically active. Otherwise, epicentral data does not delineate faults in the Clear Lake area.

Geologic mapping by various workers indicates that the Collayomi Fault is potentially active (displaces Quaternary features) in Cobb Valley northeast of The Geysers. Data on this are fragmentary.

Maximum shaking in rock commonly is specified in terms of maximum credible and maximum probable accelerations. Maximum credible acceleration at any given place is defined as the maximum acceleration that could reasonably be expected to occur, given the known geologic framework. Thus it is based entirely on the location, length and relative recentness of faults in the region surrounding a site under consideration. Maximum probable acceleration at a site is derived from statistical analysis of the recorded seismicity of the surrounding region.

Shaking is not completely described by maximum acceleration; one also needs to know its duration and spectral character (the distribution of amplitude relative to vibrational period). Spectral shapes appropriate for rock can be computed and scaled to fit maximum acceleration values from existing accelerograms.

It is both realistic and practical to use maximum probable acceleration in regions where the spatial and temporal distribution of destructive earthquakes is not well understood. Of course, most areas fall into this category, the present one included. In other words, where seismicity is largely known in a statistical way, it is sensible to predict ground motion in a probabilistic manner.

Only three major (more than a few kilometers in length) active faults are known to lie within 65 km (40 mi) of The Geysers. Faulting beyond this distance is not capable of producing significant damage. The three faults are, from west to east, the San Andreas, Healdsburg-Rodgers Creek, and Mayacmas Faults. The first two are proven seismically active; the Mayacmas Fault appears to creep (aseismic slippage), but no earthquakes are known to have occurred on it. In addition, there is evidence that the Collayomi Fault may be active, but its extent and recentness of movement are unknown. Other, shorter faults may be active or potentially active, particularly in The Geysers region. However, except for the Konocti Bay Fault, there is no clear evidence for their activity. At an arbitrary location, accelerations induced by earthquakes on shorter faults, many of which are unknown, may exceed those from events on major faults.

Maximum credible bedrock acceleration may be estimated from the length of and distance from a given fault. Empirical data relate rupture length and magnitude. Assuming that the entire mapped length of an active fault may rupture during a single event, one can estimate the maximum credible magnitude of earthquakes on particular faults. In this way, we estimate 8½ on the San Andreas Fault, 7½ on the Healdsburg-Rogers Creek Fault, and 6½ on the Mayacmas Fault. From empirical curves relating peak rock acceleration, earthquake magnitude, and distance from the causative fault, we find that maximum credible bedrock acceleration in the study region varies from about 0.7 g (acceleration of gravity) adjacent to active faults down to about 0.2 g south of Lower Lake.

Duration of strong shaking for these maximum credible events varies from about 20 seconds for M = 6½ to 40 seconds for M = 8½.

Maximum probable acceleration is derived by simply assuming that all earthquakes are randomly distributed, implicitly on unknown faults. Using magnitude-frequency parameters for 1810-1930 in the central Coast Range, maximum probable bedrock acceleration per 100 years is about 0.26 g in this area. This has a 63% chance of being exceeded in any 100-year interval, or 30% in 50 years. Design to this value would not be "conservative," in the engineering sense of the term.

A more conservative design might use the 200-year maximum probable bedrock acceleration, with a 30% chance of being exceeded in any 100-year interval (or 15% in 50 years); this is 0.42 g.

However, we expect most of the larger earthquakes to be associated with the Healdsburg or San Andreas Faults, located far beyond the region of expected geothermal development. Therefore, the accelerations given above are really too high for the given time periods, but by an unknown amount. A more sophisticated analysis, as outlined above, would certainly give smaller values of acceleration in the area of concern.

Liquefaction, differential settlement, lurch cracking, surface faulting, and landsliding comprise the various types of permanent ground deformation, or ground failure. All but faulting result from ground shaking; faulting is the proximate cause of ground shaking. Strictly speaking, liquefaction is a cause, rather than a manifestation, of ground failure.

Although permanent ground deformations may locally do serious damage to building foundations, ground shaking will cause more widespread and greater total depth damage.

Liquefaction is defined as the transformation of a granular material from a solid into a liquefied state as a consequence of increased pore-water pressures. Liquefaction may be an important problem where the groundwater table in alluvial areas is generally not more than 3 to 6 m (10 to 20 ft) deep. It may also occur in water-saturated fills, such as are often constructed for drilling pads and power plant facilities in the Mayacmas Mountains.

Landslides and land slumps are frequently triggered by strong ground shaking. In the Mayacmas Mountains extensive areas are underlain by mélange deposits of the Franciscan Formation which are particularly prone to landsliding, even without earthquake shaking. Of course, these same areas are subject to additional landslide potential under earthquake loading. Therefore, slope-stability studies for siting geothermal facilities should include analysis of the effect of earthquake shaking.

Failure by liquefaction may be a problem in saturated alluvium or fills which contain much silt to sand-sized material. Good drainage may practically eliminate potential problems in such fills.

3.4.2 Potential Induced Seismicity

Seismicity may be induced by greatly changing pore pressures of fluids in rocks, through processes of extraction and reinjection. This is most typical in areas (a) of unconsolidated sediments and (b) where intensive pressure is used to extract and inject fluid.

Neither criteria applies to The Geysers. In The Geysers area, rocks are solid, brittle and well compacted. Steam is produced without pumping, and steam condensate is injected under hydrostatic head, again without pumping. A hydrostatic column of, say, 1,500 m (5,000 ft) in a reinjection well may exert a pressure some 140 kg/sq cm (2,000 psig) greater than is the steam pressure within the reservoir. This pressure differential is believed to be insufficient to fracture reservoir rocks further than they are already fractured.

Currently, 18,000,000 lpd (4,700,000 gpd) of reinjectant are being disposed of via six wells, whose depths range from 721 to 2,452 m (2,364 to 8,045 ft). Injection rates of 4,540 lpm (1,200 gpm) per well produce no back-pressure at the well head. Injection levels are generally deeper than or equal to production depths. Injected water is not known to communicate with shallow groundwaters.

USGS monitoring of seismicity and triangulation surveys (Chasteen, 1975) has produced no information suggesting changes in seismicity. No evidence suggests that brittle limits of formation rock are being reached by hydrostatic injection.

3.5 SUBSIDENCE

Subsidence often accompanies withdrawal of fluid (oil, gas, steam, water) from unconsolidated or poorly consolidated aquifers. Geothermal field subsidence has occurred at Wairakei, New Zealand.

In addition to being dense and brittle, rocks of the Franciscan Formation at The Geysers are well indurated and devoid of intergranular pores. Fractures are random but pervasive, and may be subject to periodic sealing with silica, calcite and zeolite minerals, followed by renewed tectonic fracturing.

3.5.1 Baseline Data

Three types of data are being collected regarding possible subsidence: horizontal triangulation, precise vertical leveling, and net changes in gravity field with time. Interpretation of these data is complicated greatly by tectonic activity: it is widely agreed that this part of the Mayacmas Mountains has been uplifted by up to 910 m (3,000 ft) in Quaternary time. Seismic data (see section 3.4.2) suggest that tectonism is continuing.

USGS is conducting precise leveling and triangulation surveys, in the search for tectonic, induced seismic and subsidence effects. To date nothing is known to indicate subsidence. Gravity surveys over a 15-year period across The Geysers field suggest very tentatively that mass is not being lost from the field as rapidly as production withdrawals of steam would predict. This may reflect (a) inadequate measurements, (b) natural recharge, (c) tectonic uplift or (d) some unknown factor. Nothing suggests subsidence.

3.5.2 Potential Subsidence

On the basis of the above (sections 3.5 and 3.5.1), no subsidence is anticipated. If it occurs, it may be difficult to distinguish from tectonic effects. In any case, it is unlikely to have much effect upon the rugged, mountainous, uninhabited area of the geothermal field. It is especially difficult to see how it could cause pollutants to enter the local surface or groundwaters.

3.6 POLLUTION CONTROL TECHNOLOGY

3.6.1 Current Practices

The principal pollution control practice is reinjection of condensate into the deep reservoir. There is no intentional water discharge to surface or shallow groundwaters.

Additionally, no discharges of drilling fluids are permitted. All fluids are either evaporated to dryness or trucked to certified disposal sites. Only nontoxic materials (rock cuttings) are allowed to dry for use as fill. No permanent spoil banks are allowed. Sumps for temporary storage of drilling fluid are either plastic- or clay-lined, to prevent measurable percolation into bedrock.

Siting requirements for roads, wells and plants are very rigorous, to minimize runoff of silt-laden waters.

Accidental discharges of waters from tanks, sumps or other sources do occur, but control of these discharges is reasonably good.

Prior to 1972, volatiles (water vapor, hydrogen sulfide, carbon dioxide, ammonia, etc.) were liberated to the atmosphere. The emission of hydrogen sulfide to the atmosphere from geothermal power production at The Geysers rose from 30 lb/hr in 1960 to 1,670 lb/hr in 1975 (Leibowitz, 1977).

Blowouts of geothermal wells may cause atmospheric and/or groundwater pollution. Up to 50% of the wells drilled at The Geysers are sited on old landslides (Bacon, 1976), which aggravates the blowout problem, since well casings may be sheared by reactivated landslides. Many of the old landslides have temporarily stabilized; however, each wet winter season charges the slopes and slides with high moisture which can cause renewed slide activity.

Union Oil Company well No. GDC 65-28, completed in 1968 on the upper part of a large landslide, blew out in March 1975. Bacon (1976) believes this event may be directly related to renewed movement of the slide. After the blowout Union Oil initiated a program to rework their early wells and bring them up to present well completion and engineering standards in order to prevent this type of blowout.

3.6.2 Anticipated Technology

It is anticipated that discharge requirements set by the state ARB and the local APCD for hydrogen sulfide for each plant and for wells being tested will be complied with in the future by designing new plants with hydrogen sulfide controls and by installing retrofit abatement systems in preexisting plants. Research by PG&E (Allen and McCluer, 1975) has indicated that the following methods are practicable for hydrogen sulfide abatement:

1) Direct injection of sulfur dioxide into cooling waters to oxidize hydrogen sulfide to sulfur by the Claus reaction: $2H_2S + SO_2 \rightarrow 3S + 2H_2O$.

2) Simultaneous injection of sulfur dioxide and air.

3) Addition of a metal catalyst, iron, to the cooling waters, to promote direct oxidation of hydrogen sulfide to elemental sulfur: $2H_2S + O_2 \rightarrow 2S + 2H_2O$.

4) Addition of a chelated iron compound (Cataban, manufactured by the Rhodia Corporation) to catalyze the direct oxidation of hydrogen sulfide by the dissolved oxygen.

Other research (Castrantas, et al. 1976) has developed hydrogen peroxide abatement processes by sulfide oxidation, illustrated by the equation

$$H_2S + H_2O_2 \rightarrow 1/x\ S_x + 2H_2O$$

in acid or neutral solutions and

$$S^{-2} + 4H_2O_2 \rightarrow SO_4^{-2} + 4H_2O$$

in alkaline solutions.

Cooling tower tests of these abatement alternatives are currently underway.

At the gas ejector, scrubbing with an iron catalyst, and burning of hydrogen sulfide to sulfur dioxide, followed by dilution of sulfur dioxide in water, appear practicable. Tests also are underway here.

Geysers Unit 11 is the only geothermal power plant in the world to have ever been designed with hydrogen sulfide abatement in mind. Its present emissions per kilowatt-hour are lower by nearly a factor of three than the average emissions from preexisting plants Units 1 through 10, and the plant has an abatement efficiency of approximately 70% (Weres, 1976). Surface condensers are to be employed in Units 13, 14 and 15, with predicted abatement levels of 80 to 90% (Weres, 1976). In addition, measures are being taken to reduce the amount of steam vent emissions during power unit shutdowns. PG&E hopes to hold emissions of hydrogen sulfide to permissible levels, but does not expect to eliminate all discharge.

Other than condensate reinjection and hydrogen sulfide abatement, no additional treatment is anticipated.

REFERENCES

Allen, G. W. and H. K. McCluer. Abatement of Hydrogen Sulfide Emissions from The Geysers Geothermal Power Plant; in Second United Nations Symposium on the Development and Use of Geothermal Resources, v. 3, p. 1313-1316, 1975.

Anderson, S. O. Environmental Impacts of Geothermal Resource Development on Commercial Agriculture: A Case Study of Land Use Conflict; in Second United Nations Symposium on the Development and Use of Geothermal Resources, Proceedings, v. 3, p. 1317-1322, 1975.

Bacon, C. F. The Recent Blowout of a Geothermal Well at The Geysers Geothermal Field; in Geothermal Environmental Seminar - 1976, Lake County, California, F. L. Tucker and M. S. Anderson, eds., 1976.

Budd, C. F. Steam Production at The Geysers Geothermal Field; in Geothermal Energy, P. Kruger and C. Otte, eds., Stanford University Press, p. 129-144, 1973.

California Department of Water Resources. Lake County Investigation Bulletin 14, 197 p., 1957.

Castrantas, H. M., T. A. Turner and R. W. Rex. Hydrogen Sulfide Abatement in Geothermal Steam; in Geothermal Environmental Seminar - 1976, Lake County, California, F. L. Tucker and M. S. Anderson, eds., 1976.

Chasteen, A. J. Geothermal Steam Condensate Reinjection; in Second United Nations Symposium on the Development and Use of Geothermal Resources, Proceedings, v. 3, p. 1335-1336, 1975.

Finney, J. P. Design and Operation of The Geysers Power Plant; in Geothermal Energy, P. Kruger and C. Otte, eds., Stanford University Press, p. 145-162, 1973.

Geonomics, Inc. Baseline Geotechnical Data for Four Geothermal Areas. U.S. Environmental Protection Agency, Office of Research and Development, in press.

Hearn, B. C., J. M. Donnelly and F. E. Goff. Geology and Geochronology of the Clear Lake Volcanics, California; in Second United Nations Symposium on the Development and Use of Geothermal Resources, Proceedings, v. 1, p. 423-428, 1975.

Leibowitz, L. P. Projections of Future Hydrogen Sulfide Emissions and Geothermal Power Generation: The Geysers Region, California; in Geothermal: State of the Art, Geothermal Resources Council, Transactions, 1977.

Reed, M. J. and G. E. Campbell. Environmental Impact of Development in The Geysers Geothermal Field, USA; in Second United Nations Symposium on the Development and Use of Geothermal Resources, Proceedings, v. 3, p. 1399-1410, 1975.

Roberson, C. E. and H. C. Whitehead. Ammoniated Thermal Waters of Lake and Colusa Counties, California. USGS Water Supply Paper 1535-A, 11 p., 1961.

Upson, J. E. and F. Kunkel. Ground Water of the Lower Lake-Middletown Area, Lake County, California. USGS Water Supply Paper 1297, 83 p., 1955.

Weres, O. Environmental Implications of the Exploitation of Geothermal Brines; in Geothermal Environmental Seminar -1976, Lake County, California, F. L. Tucker and M. S. Anderson, eds., 1976.

SECTION FOUR

KLAMATH FALLS

4.1 INTRODUCTION

4.1.1 Summary

Some 400 shallow wells are used for space heating at the Klamath Falls and Klamath Hills thermal areas. Of these, only a handful produce geothermal fluid to the surface; the remainder utilize heat-exchanging with cool meteoric water in the well bore. Well depth averages about 150 m (500 ft); deepest wells reach 550 m (1,800 ft).

Recorded temperatures reach 113°C (235°F); water geothermometry suggests 140°C (280°F) to possibly over 150°C (300°F) as the temperature of a deeper (1 km [0.6 mi]) reservoir.

Consumed heat is equivalent to 5.6 MW average annual use, with peak demand reaching 56 MW.

Water chemistry is relatively benign, with TDS of 500 to 1,000 ppm, moderate (50 ppm) chloride, low boron and fluoride (about 1 ppm each), and no reported toxic substances. The system is not gassy.

The area exhibits low seismicity, and appears to have little potential for induced seismicity as a result of field production. Subsidence is not recognized.

4.1.2 Background

Data for this study come from many sources. Principal among these are reports by the USGS and the Oregon State Engineer's Office. These are supplemented by brief reports by the Oregon Department of Geology and Mineral Industries, and by fragmentary data from private sources, researchers at Oregon State University and Oregon Institute of Technology (OIT), and company records of GeothermEx, Inc.

These data mainly deal with surface geology and hydrology, the shallow groundwater system, utilization of thermal water at Klamath Falls, and results of exploration for geothermal resources. There are limited data on water chemistry and seismicity.

Data are lacking on the deep geothermal system: its chemistry, enthalpy, state, extent and producibility. Data are scarce concerning possible subsidence, induced seismicity and likely pollutants from a geothermal system.

A canvass of wells is presently being conducted by the USGS and OIT. However, very little is known other than well locations, depths and temperatures.

4.2 GEOTHERMAL SYSTEM

4.2.1 Definition of System

Klamath Falls, a city of nearly 20,000 inhabitants, is located in the southern part of Klamath County in southern Oregon (Fig. 4.1) within a large, compound graben known as the Klamath Basin. The basin contains numerous thermal springs and areas of thermal wells, the most significant of which are:

1) a 5-km (3-mi) long northwest trending zone of thermal springs and wells within Klamath Falls city;

2) a 5-km (3-mi) long northwest trending zone of thermal wells on the southwest flank of the Klamath Hills, some 19 km (12 mi) south of Klamath Falls;

3) a stream canyon at Olene Gap, about 13 km (8 mi) southeast of Klamath Falls, the site of thermal springs and wells, and

4) the east side of Eagle Point, a peninsula in Klamath Lake 24 km (15 mi) northwest of Klamath Falls, the site of thermal springs.

Mildly thermal waters are found at several other places in the Klamath Basin. All told, these form a discontinuous and en-echelon, principally northwest trending zone of thermal waters nearly 48 km (30 mi) long. Indeed, possible structural extensions of the Klamath Basin in northern California are indicated by occasional thermal wells.

By far the most important of these thermal anomalies are those at Klamath Falls and Klamath Hills, with those at Klamath Falls being better known and more extensively developed. Manifestations include thermal springs (Klamath Falls, Olene and Eagle Point) at temperatures from about 32°C (90°F) (Eagle Point) to near boiling (Klamath Falls); shallow thermal wells (Klamath Falls, Klamath Hills, Olene and elsewhere) producing water just above ambient nonthermal groundwater temperatures (16°C [60°F]) or higher to as high as 113°C (235°F) (Klamath Falls); and a few shallow wells that produce steam (Klamath Falls).

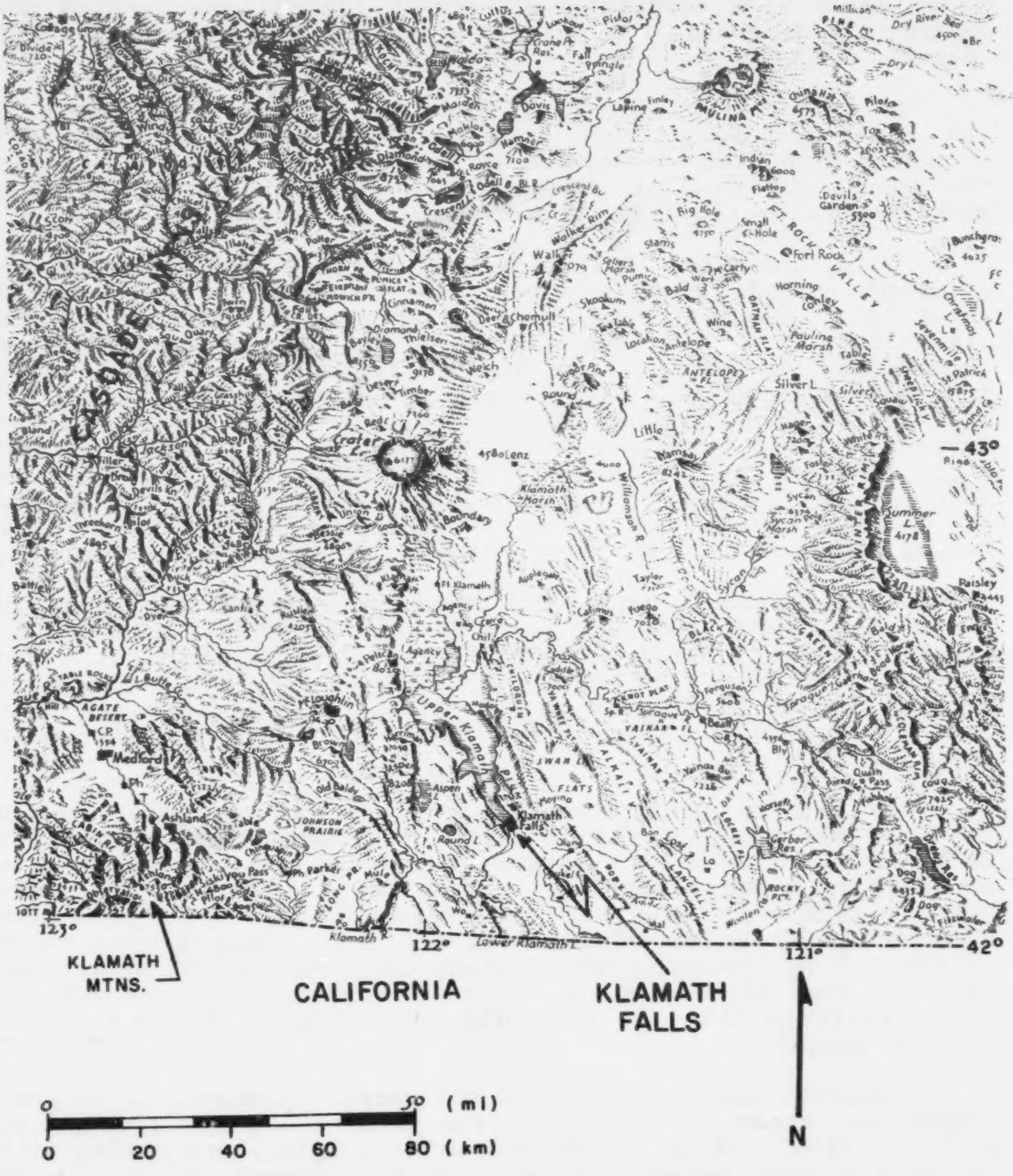

CASCADE
Crater L.
Klamath Marsh
Medford
Ashland
Klamath Falls
Upper Klamath L.
Summer L.
Fort Rock
FT. ROCK VALLEY
PAULINA
Lower Klamath L.
—43°
123°
122°
121°
42°
KLAMATH MTNS.
CALIFORNIA
KLAMATH FALLS
0
50 (mi)
0
20
40
60
80 (km)
N

Figure 4.1 Physiography of Klamath Falls, Oregon vicinity (modified from Raisz, 1955)

Altogether, at least 400 features produce thermal fluid, the majority of them only slightly above ambient nonthermal groundwater temperatures. Most wells with temperatures above 60°C (140°F) are in Klamath Falls city or suburbs. At least three wells with temperatures to 82°C (180°F) are located not farther than about 1.6 km (1 mi) from a major fault zone (Sammel, 1976).

The association of these thermal features with faults of the Basin and Range type (normal, down on the valley side) suggests that deep convective circulation of meteoric water is the source of heat for the geothermal system. Nothing clearly suggests a magmatic heat source.

Fluid chemistry (silica concentration, sodium-potassium-calcium ratios) is suggestive of a reservoir temperature of about 140°C (280°F) which would be inadequate for generation of electricity. Temperatures this high have not been encountered in drilling to date; therefore, the depth to waters of this temperature is unknown. Speculation suggests about 1 km (3,300 ft) to the high temperature reservoir, with convective circulation reaching perhaps 3 to 4 km (10,000 to 13,000 ft) along major faults. This assumes a conductive gradient of perhaps 35°C per km (1°F per 100 ft), which is "normal" for most areas of the western United States. In the event of higher than normal gradients, convective circulation might be shallower.

Wells in the Klamath Falls area commonly are less than 210 m (700 ft) deep, with many wells being less than 75 m (250 ft), especially along fault scarps. The wells producing wet steam are less than 46 m (150 ft) in depth, along the trace of a fault in the center of Klamath graben. Apparently, steam has collected there as the result of boil-off from a deeper hot water aquifer.

The deepest thermal wells are those at OIT campus, which reach to 550 m (1,800 ft) in depth, and have a temperature of 88°C (190°F). Deep oil tests elsewhere in the region may have as high or higher temperatures, but do not involve the geothermal convective system. A geothermal test hole near the Klamath Hills geothermal zone was drilled to more than 1,700 m (5,500 ft) by Thermal Power Company in 1976. Although no temperature logs or chemical analyses are available to the public, it is believed that the hole did not encounter the geothermal aquifer sought.

Reservoir fluid probably is hot water. However, it is possible that steam is ascending from greater depths, perhaps as boil-off from a still deeper hot water aquifer, and mixing with descending cool meteoric water. This is based principally on the relatively dilute chemical character of the hot water as known.

Chemically (Table 4.1), the cool ground and surface waters are calcium magnesium bicarbonate, with very low TDS (often less than 100 ppm). Chloride, sulfate, boron and fluoride are present at less than 1 ppm. With increasing temperature, waters show:

1) increased TDS, commonly reaching 500-700 ppm, and occasionally exceeding 1,000 ppm;

2) increase of chloride and especially sulfate relative to bicarbonate;

3) increase of sodium relative to calcium, and absolute drop in magnesium, probably as a result of fixation in clay minerals;

4) only a mild increase in boron and fluoride, with values rarely exceeding 1 ppm of either.

The system does not appear to be very gassy, although gas analyses are almost nonexistent.

The Klamath Hills system appears similar, except that sulfate values appear to be lower than at Klamath Falls.

Crude calculations based on mixing variable fractions of low TDS, calcium magnesium bicarbonate water with hotter, more concentrated geothermal waters lead to the conclusion that true reservoir equilibrium temperature in the Klamath Hills system may be above 150°C (300°F). This is compatible with a 55°C per km (2°F per 100 ft) gradient to 3 km (10,000 ft).

Presently, about 500 hundred homes, offices, commercial buildings, schools, churches and greenhouses are heated by geothermal water from the shallow system from some 400 separate shallow wells (Lund, et al. 1975). Well water ranges from 38° to 110°C (100° to 230°F) in temperature as produced. The energy consumption from this system is equivalent to 5.6 MW average annual use, with a peak load equivalent to 56 MW. Although it is widely believed that the system has the capacity to produce far more than this, there is no factual basis for making a quantitative estimate.

Well costs averaging about $10,000 have kept many homeowners and small businessmen from installing geothermal well systems. However, rising fuel costs have heightened interest in such systems and increased utilization can be anticipated in coming years.

TABLE 4.1 CHEMICAL ANALYSES OF WATERS FROM SPRINGS AND WELLS KLAMATH BASIN, OREGON

Name of Spring or Well	Sample Location T, R, Sec.	Date of Sample	Temp., °C	pH	Specific Conductance µmho/cm	TDS Evaporation
Eagle Point Spring	36-7-23dca	4-6-75	85	8.3	305	-
Shell Rock Spring	38-8-27	8-6-75	7	6.4	110	-
Cabin Spring	37-8-26	8-5-72	11	5.5	-	-
Hummingbird Spring	37-9-6bcd	4-2-75	11	8.3	135	-
Neubert Spring	37-9-7adc	8-6-75	10	8.2	160	-
Well, 98.6 feet deep	37-9-9dcc	8-6-75	10	6.8	150	158
OIT Well #6	38-9-20adb	3-31-75	79	8.2	1050	-
Mer-Bell-Dairy	38-9-28ccc	1-24-55	81	8.8	1160	-
J. E. Ericson	38-9-28cdc	19-55	83	8.7	1230	-
Oregon Water Corp.	38-9-30acb	8-8-75	15	8.0	250	-
Keno Spring	38-12-14	10-16-75	11	7.7	100	72
Alfred Jacobson	39-9-34	5-20-74	30	7.6	290	-
Weyerhaeuser Well #4	39-9-18	10-11-73	22	8.3	200	-
U. S. Air Force	40-7-11ccc	5-27-74	15	8.6	340	-
Dave O'Connor	40-9-23bab	5-7-74	24	7.6	260	-
O. H. Osborn	40-9-27cda	5-31-74	90	9.5	920	-
Anderson Well	40-9-27	11-8-75	27	8.0	450	286
Abe Boehm	40-9-28aca	5-30-74	25	7.1	2700	-
Liskey Well	40-9-34aca	5-9-74	93	8.9	1030	724
Tulana Farms Spring	41-8-5cbb	8-8-75	13	6.9	115	-

(continued)

TABLE 4.1 (continued)

Name of Spring or Well	Concentrations (milligrams per liter) SiO_2	Na	K	Ca	Mg	HCO_3	CO_3	SO_4	Cl	F	B
Eagle Point Spring	38	62	5.7	0.6	0.1	136	0	<2	16	.75	.14
Shell Rock Spring	32	5.9	1.5	8.1	3.9	50	0	<2	<1	.10	.05
Cabin Spring	29	5.9	1.6	11.2	5.1	94	0	<1	<2	.10	.10
Hummingbird Spring	18	8.0	1.2	9.2	6.5	84	0	<2	1	.10	.07
Neubert Spring	21	7.0	1.2	10.6	8.2	96	0	<2	1	.10	.05
Well, 98.6 feet deep	24	7.6	1.3	12.1	7.2	94	0	<2	1	.11	.05
OIT Well #6	31	195	3.9	24.2	0.1	44	0	400	58	1.45	1.0
Mer-Bell-Dairy	81	213	4.2	23	0	32	8	403	54	1.2	.96
J. E. Ericson	87	221	4.4	25	0	32	8	1.2	56	1.6	.91
Oregon Water Corp.	27	22	-	14.4	0.8	-	-	0.4	4.5	.01	-
Keno Spring	40	4.1	3.0	7	6.2	73	0	13	1.8	.08	.05
Alfred Jacobson	65	69	12	160	2.4	160	0	4	7.9	.10	.50
Weyerhaeuser Well #4	16	32	3.3	10	1.9	115	4.5	2.3	4	.11	.09
U. S. Air Force	31	17	1.6	24	17	200	3	14	2.3	0	0.9
Dave O'Connor	42	32	8.1	12	6.6	130	0	270	9.1	0	0
O. H. Osborn	90	140	4.1	15	0	37	9	36.2	56	1.5	.77
Anderson Well	41	88	2.5	5.0	0.1	165	6.0	300	23	.40	.15
Abe Boehm	100	480	18	180	47	1460	1	360	170	.20	1.4
Liskey Well	90	200	4.0	15	0.1	48	2	2	59	1.5	.65
Tulana Farms Spring	24	5.7	1.2	9.2	4.9	60	0	-	1	.07	.05

(continued)

TABLE 4.1 (continued)

				Cl:	Ionic Ratios				
			Na+K	Total	Cl	Cl	Cl	HCO_3	Alk
Name of Spring or Well	Na:K	Na:Ca	Ca+Mg	Alk.	SO_4	F	B	B	SO_4
Eagle Point Spring	18.51	180.99	149.60	.40	21.70	11.45	34.87	172.31	53.61
Shell Rock Spring	6.70	12.70	.82	.07	1.36	5.42	6.80	177.38	19.71
Cabin Spring	6.30	0.90	.50	.10	-	-	-	269.60	-
Hummingbird Spring	9.95	1.15	.55	.04	1.35	5.42	7.63	340.56	62.02
Neubert Spring	9.96	1.10	.61	.04	1.35	4.94	7.63	333.47	37.06
Well, 98.6 feet deep	1.70	1.51	1.08	.04	2.72	39.40	-	-	72.39
OIT Well #6	85.1	14.05	14.12	4.53	.39	21.44	17.70	7.80	.09
Mer-Bell-Dairy	86.50	16.20	16.40	4.63	.36	24.10	17.16	7.39	.08
J. E. Ericson	76.80	15.40	15.61	-	.35	18.80	18.78	7.80	.07
Oregon Water Corp.	16.98	2.66	1.33	-	10.0	239.50	-	-	-
Keno Spring	2.32	1.02	.59	.06	12.18	21.85	10.97	259.50	200.10
Alfred Jacobson	9.78	.75	.81	.17	1.64	42.20	4.82	56.76	9.70
Weyerhaeuser Well #4	16.40	5.58	4.51	.12	2.71	19.78	13.56	235.52	23.55
U. S. Air Force	18.07	1.23	.60	.04	2.71	-	.08	400.08	69.54
Dave O'Connor	6.72	4.65	2.80	.24	1.76	-	-	-	7.31
O. H. Osborn	7.88	2.21	2.49	4.19	.56	20.01	22.19	10.06	.13
Anderson Well	59.70	30.80	30.71	.46	1.72	32.80	46.91	194.20	3.72
Abe Boehm	45.35	4.65	3.32	.40	1.53	455.48	37.05	185.11	3.83
Liskey Well	75.00	16.13	14.81	3.64	.52	18.40	28.17	15.40	.14
Tulana Farms Spring	8.10	1.08	.65	.06	.50	7.83	6.10	212.85	9.72

4.2.2 Potential Pollutants

The principal pollutant is heat; this is derived from all wells, whether heat-exchangers (see 4.2.1, above) or direct consumers of geothermal fluid. Those holes involving heat-exchange do not discharge any mineralized water, as none is produced from the wells. Only those few holes consuming geothermal reservoir fluid have any geothermal discharge.

4.3 WATER POLLUTION POTENTIAL

4.3.1 Summary of Baseline Water Characteristics

Klamath Basin groundwaters fall into two main chemical groups. Cool wells and springs are of the calcium magnesium bicarbonate type with low TDS (about 55 ppm). The second type of water, occurring in warm and hot wells and springs, mostly within the basins of the Klamath graben, is sodium bicarbonate chloride sulfate water with TDS averaging 700 ppm (and reported as high as 4,000 ppm). Boron and fluoride concentrations increase with temperature. For a detailed discussion of water characteristics of Klamath Basin, refer to Geonomics (in press).

Water pollution data are very scarce, incomplete and probably meaningless. They show principally that pulp and paper operations at Klamath Falls and agricultural irrigation discharge more pollutants and possibly toxic substances than the geothermal system can be shown to contain. Among these industrial and agricultural wastes are pesticide residue, various phosphate fertilizers, and sulfate and chloride ions. Partial analyses of water from Klamath Lake and Klamath River show indications of these.

4.3.2 Potential Water Pollutants

The principal pollutants from this discharge are chloride ions (perhaps 50 to 60 ppm, Table 4.1) and boron, with about 1 ppm on the average. In comparison, local cool surface waters average less than 1 ppm boron and 1 to 10 ppm chloride.

Other polluting constituents are not recognized from the scattering of partial chemical analyses available to this study. However, no data are available concerning metals or other trace element contents of these waters. When these additional data are obtained, the pollution potential may be altered.

4.3.3 Potential Pollution Mechanisms and Pathways

Direct discharge from thermal wells goes into local surface waters. Most wells do not directly produce the reservoir fluid, but utilize heat-exchanging in the well with cool, meteoric water supplied through the municipal water system. The heated municipal water is discharged to the sewer system when depleted of its heat. Those wells (principally OIT and Klamath Hills) consuming reservoir fluid at the surface, dispose of the heat-depleted fluid in a similar manner.

4.3.4 Level of Potential Pollution

No reason is seen for an increase in pollutants, unless either:

1) New wells are allowed to discharge to the surface instead of being heat-exchanged with cool meteoric water; or

2) Wells are drilled into deeper aquifers (perhaps 900 m [3,000 ft] or deeper).

The latter seems unlikely in the near future, because of the cost of the deeper drilling, and the general lack of interest in exploration for a deep geothermal aquifer for generation of electricity. If it occurs, new studies of chemistry, heat content and pollutants will be required.

4.4 SEISMICITY

4.4.1 Summary of Baseline Seismicity and Seismic Risk

Throughout the Pacific Northwest, including Klamath Basin, very few seismograph stations operated until the year 1962. Earthquakes of magnitudes smaller than 4½ or 5 either were not recorded at all, or were not recorded at sufficient stations to permit instrumental location of epicenters and determination of magnitude. Thus, nearly all pre-1962 shocks were located using felt-reports, which are highly dependent upon the distribution of population and time of day of occurrence. Also, the "size" of these events was based on a crude, graduated rating of effects.

Therefore, the earthquake history of this region is poorly known as to the occurrence of noninstrumental epicenter location and size of smaller shocks ($M \leq 5$). For this reason, correlation of seismicity with particular faults, and determination of magnitude-frequency curves for various areas, cannot be done with much confidence.

Most of Oregon, and adjacent parts of Idaho, Nevada and California, form a large region of low seismicity in comparison with many parts of the western United States. Historically, no major, destructive earthquakes have occurred in Oregon, nor has any instance of surface faulting been reported. Moderate seismicity characterizes the Portland-Willamette Valley area of northwestern Oregon; however, the rest of the state exhibits lower or negligible seismicity. Slight seismicity has been reported near Klamath Falls, but not elsewhere in Klamath Basin. Berg and Baker (1963) reported five small shocks, with intensity IV, at Klamath Falls during the years 1947 to 1951.

Earthquake risk is poorly known because of the extremely low seismicity and inadequate reporting. Couch and Lowell (1971) have analyzed earthquake occurrence in Oregon, and described the seismicity of several physiographic provinces. One of the provinces is the Basin and Range, which includes Klamath Basin.

Very limited data suggest a rate of energy release of 8.8 x 10^{16} ergs/yr for the period 1870 to 1970 (Couch and Lowell, 1971); this figure is probably too low, due to the lack of shocks being reported between 1870 and 1906. In any case, this rate of energy release is equivalent to the occurrence of one M~3.3 earthquake per year per 10,000 sq km (3,900 sq mi); or to one shock of M~5 per 50 years per 10,000 sq km (3,900 sq mi). Clearly, this area has exhibited very low seismicity compared to the seismicity of central coastal California, which may be expressed as ten M~5 shocks per 50 years per 10,000 sq km (3,900 sq mi).

Based upon the above data, the maximum probable earthquake acceleration per 100 years at a given site in the Klamath Basin is expected to be about 0.07 g. Therefore, earthquake risk to well-engineered facilities in this area is quite low in comparison with many other areas.

No individual faults are mapped as presently active or as disturbing late Quaternary deposits. However, fault movement was intense in Pliocene and early Pleistocene time, and the potential for renewed movement may exist.

4.4.2 Potential Induced Seismicity

Seismicity may be induced by change of pore pressures, resulting from (a) withdrawal of fluid from rocks that are poorly consolidated, with abundant pore space, or (b) injection of fluid under high pressure into brittle rocks of limited porosity. Neither condition is recognized at Klamath Falls.

Withdrawal is limited to a few wells on the OIT campus and at Klamath Hills. Other wells involve in situ heat-exchanging, without production of fluid from the geothermal reservoir. No injection takes place.

Unless the conditions of utilization change radically, induced seismicity is not anticipated.

4.5 SUBSIDENCE

Subsidence is reported from many localities where fluid (oil, gas, steam, water) is produced from poorly consolidated rocks or sediments. The case at the Wairakei, New Zealand, geothermal field is well known.

4.5.1 Baseline Data

There has been no systematic attempt to collect data from leveling or triangulation surveys to determine if subsidence is occurring at Klamath Falls.

4.5.2 Potential Subsidence

If production of geothermal fluid increases, or continues for a very long time at its limited rate, some surface subsidence may be noted. Production currently is limited to a few hundred liters per minute along the Klamath Hills and on the OIT campus. Some declines in static and pumped water levels have been reported informally at OIT, but no quantification has been possible. At these production levels, it may be decades before ground subsidence is recognized.

4.6 POLLUTION CONTROL TECHNOLOGY

4.6.1 Current Practices

Pollution appears so minimal, that nothing is done at present to control it. Probably the single most significant indirect control mechanism is the practice of heat-exchanging in all but a handful of the 400 thermal wells in Klamath Falls and Klamath Hills, thus preventing discharge of any geothermal fluid.

4.6.2 Anticipated Technology

Changes in practice are not anticipated. Perhaps in future years it will be necessary to ensure that all nonthermal aquifers are cased and cemented off from the thermal aquifers in every well. However, the value to be gained from this may be minimal, as the thermal water is of relatively good quality.

REFERENCES

Berg, J. W. and C. D. Baker. Oregon Earthquakes, 1841-1958. Seis. Soc. Amer. Bull. v. 53, p. 95-108, 1963.

Couch, R. W. and R. P. Lowell. Earthquakes and Seismic Energy Release in Oregon. Oregon Dept. Geol. and Min. Industries, Ore Bin, v. 33, No. 4, p. 61-84, 1971.

Geonomics, Inc. Baseline Geotechnical Data for Four Geothermal Areas in the United States. United States EPA, Environmental Monitoring and Support Laboratory, Las Vegas, Nevada, in press.

Lund, J. W., G. G. Culver and L. S. Svanevik. Utilization of Intermediate-temperature Geothermal Water in Klamath Falls, Oregon; in Second United Nations Symposium on the Development and Use of Geothermal Resources, Proceedings, v. 2, p. 2147-2154, 1975.

Raisz, E. Landform Map of Oregon. State Department of Geol. and Min. Ind., Portland, Oregon, 1955.

Sammel, E. A. Hydrologic Reconnaissance of the Geothermal Area Near Klamath Falls, Oregon. USGS Open File Report WRI 76-127, 1976.

SECTION FIVE

RIO GRANDE RIFT ZONE

5.1 INTRODUCTION

For discussion purposes the Rio Grande Rift divides conveniently into four parts, each with distinctive geothermal features and energy potential (Fig. 5.1). In "downstream" order these parts are:

1) the San Luis Basin,

2) the Jemez (Valles Caldera) area,

3) the Socorro-La Jencia Basin, and

4) the southern Rio Grande Rift area.

These areas represent markedly different levels of geothermal potential and consequently different levels of potential environmental impact resulting from development.

The baseline data report of this series (Geonomics, in press) described the climatology, geology, hydrology and seismology of the Rio Grande Rift in general. That study has led us to focus on the Jemez (Valles Caldera) area. Consequently, more detailed baseline data for the Jemez area will be developed here, with emphasis on potential environmental impacts.

The Jemez River Basin includes both the Union Oil Company's announced geothermal discovery (in the Valles Caldera) and the hot dry rock experiment being carried out nearby by the Los Alamos Scientific Laboratory, University of California (LASL). From the standpoint of anticipating the potential environmental impact of geothermal development, sufficient data exist only for the Jemez area. Either the hot dry rock experiment or the Union Oil Company field could become operational geothermal energy sources within a few years. The need to understand the environmental impact of these operations could become urgent within a relatively short time; whereas the environmental impact of geothermal development in the other areas lies years to decades in the future. Therefore, we have focused only on the Jemez area in this report.

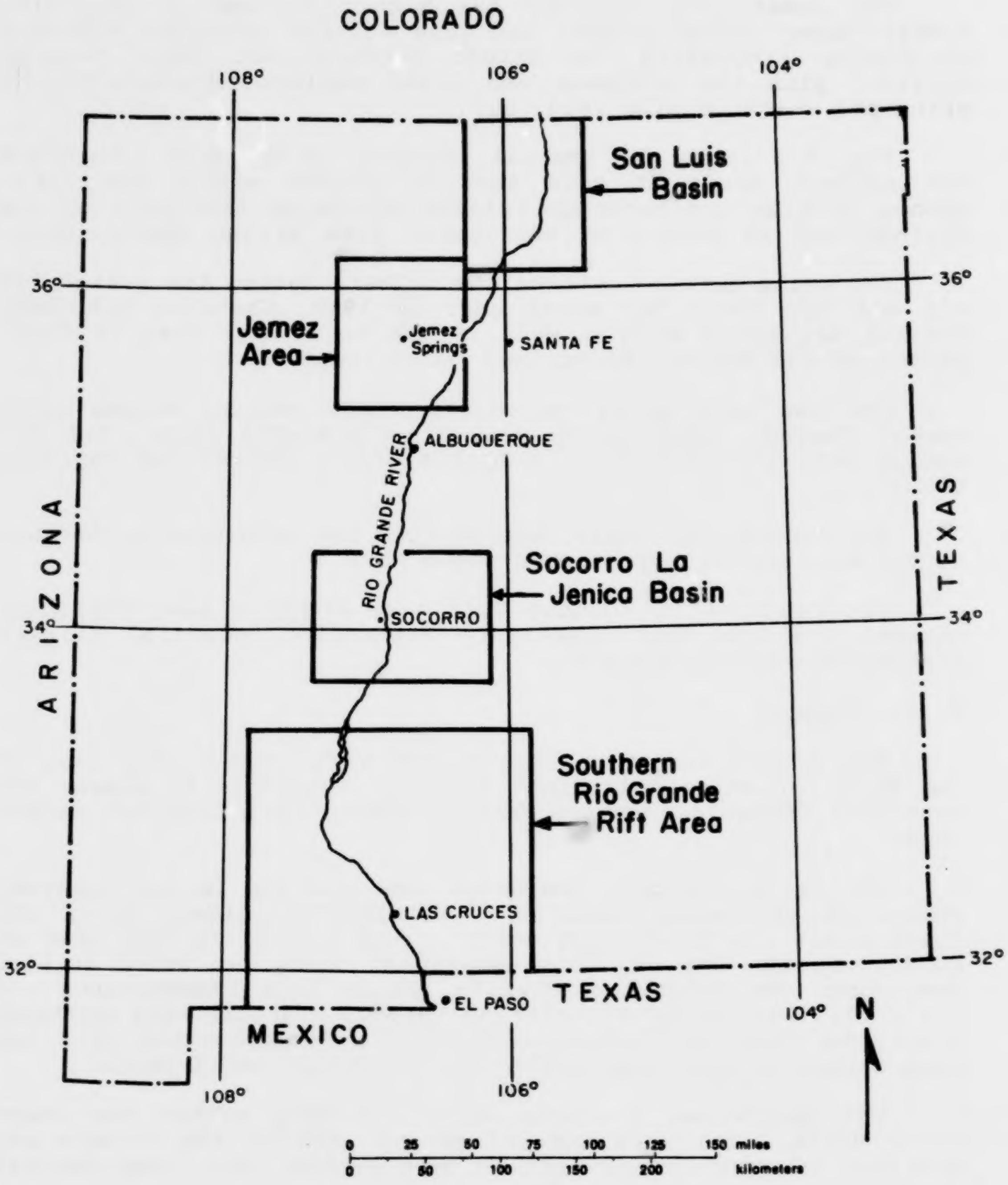

COLORADO
108°
106°
104°
San Luis Basin
36°
36°
Jemez Area
Jemez Springs
SANTA FE
ALBUQUERQUE
RIO GRANDE RIVER
ARIZONA
TEXAS
Socorro La Jenica Basin
SOCORRO
34°
34°
Southern Rio Grande Rift Area
LAS CRUCES
32°
32°
EL PASO
TEXAS
MEXICO
104°
N
108°
106°
0 25 50 75 100 125 150 miles
0 50 100 150 200 kilometers

Figure 5.1 Thermal areas of the Rio Grande Rift in New Mexico

The Jemez area includes the high mountains of the relatively young Valles Caldera and some smaller and older volcanic structures (including the Toledo Caldera) and their related valleys, plus the plateaus and river valleys adjacent to the principal volcanic pile (Fig. 5.2).

Fig. 5.3 shows the thermal features of the area. Warm and hot springs occur at more than 20 places within the area. Carbon dioxide and hydrogen sulfide discharge from many of the springs and an extensive solfataric area within the caldera.

Two wells drilled outside the caldera during the search for oil and gas found hot water and, in 1960, Westates Petroleum Company drilled a wildcat well in the solfataric area in Alamo Canyon of the Valles Caldera and found steam.

The San Luis Basin represents a not unusual enigma--just enough thermal activity to make it a possible target but not enough activity to make it a high priority target for exploration.

The Socorro-La Jencia area excites the imagination, because it may be underlain by a large magma body.

The Southern Rio Grande Rift area exhibits many surficial thermal features that constitute attractive potential targets for geothermal exploration.

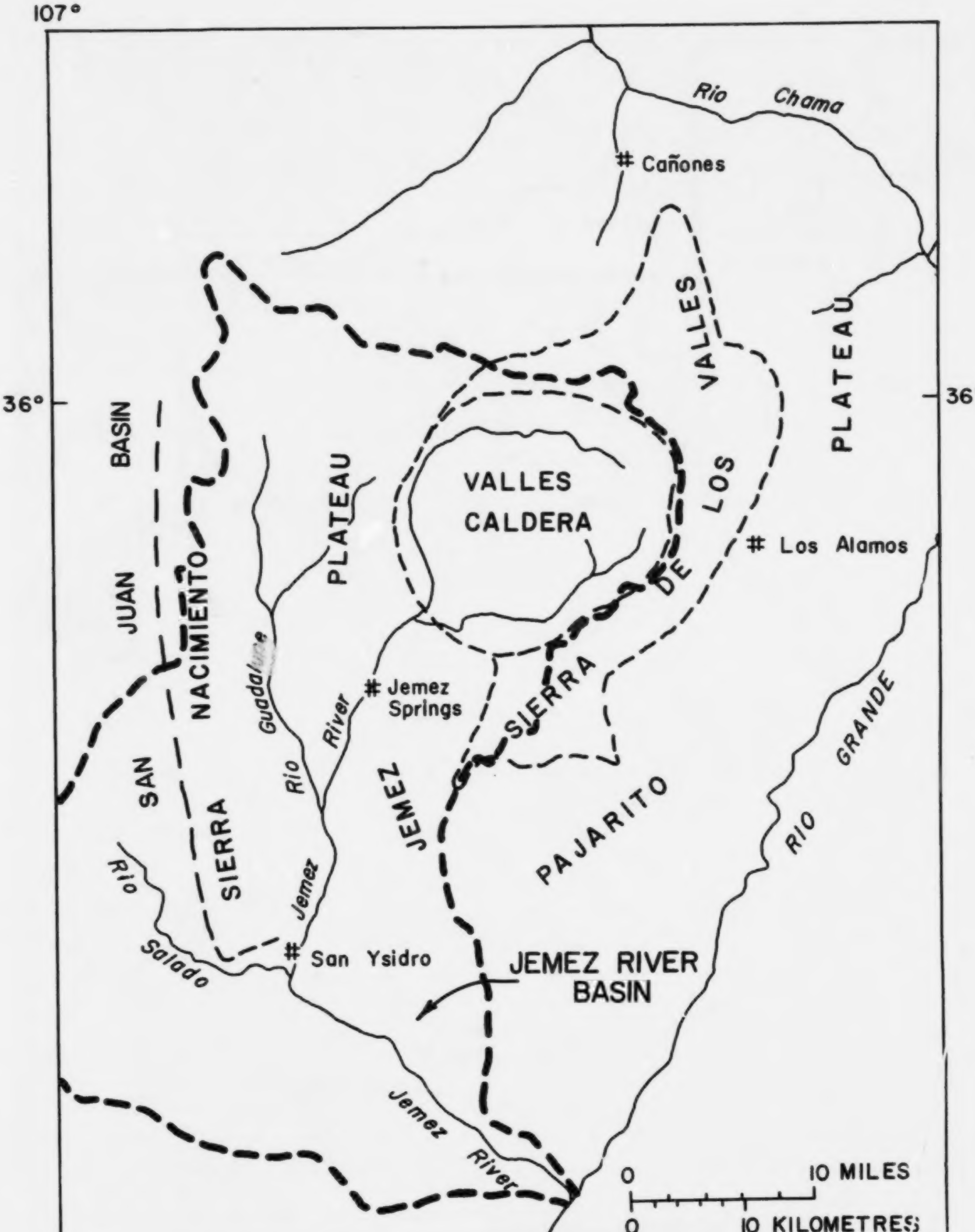
5.1.1 Summary

The Jemez area of the Rio Grande Rift is the only area in the Rift for which sufficient data are available to assess the potential subsurface environmental impacts of geothermal development.

The Valles Caldera dominates the area and is the apparent center of geothermal activity. Within the caldera Union Oil Company has six production wells. West of the caldera LASL is conducting the hot dry rock experiment using two wells drilled deep into the underlying granite, where rock temperatures are 200°C (392°F). Water circulating through hydraulically produced fractures from the injection well to the production well has been warmed to more than 100°C (212°F) during short tests.

The geothermal features occur entirely within the Jemez River Basin. The warm and hot waters outside the caldera are mixtures of circulating shallow groundwater and "deep thermal groundwater" from the caldera.

Potential pollutants due to production of thermal fluids include arsenic, boron, fluoride and hydrogen sulfide. Injection of waste fluids into wells within the caldera should remove any hazard; release at the surface would be hazardous.


107°
36°
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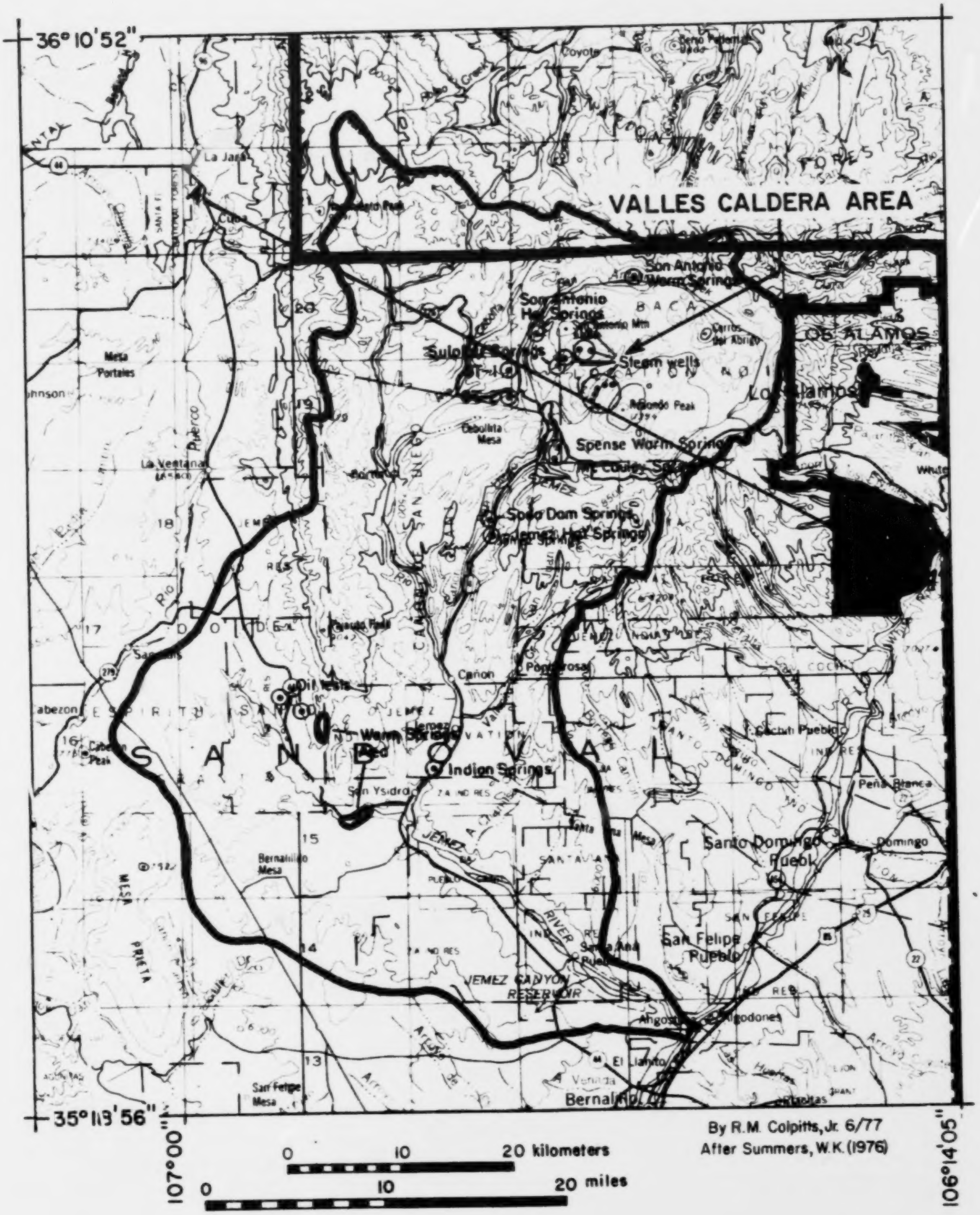
Rio Chama
Cañones
VALLES CALDERA
VALLES
LOS
DE
SIERRA
PLATEAU
Los Alamos
SAN JUAN BASIN
SIERRA NACIMIENTO
PLATEAU
Rio Guadalupe
Jemez Springs
Rio River
JEMEZ
PAJARITO
RIO GRANDE
Rio Salado
Jemez
San Ysidro
JEMEZ RIVER BASIN
Jemez River
0 10 MILES
0 10 KILOMETRES
After Trainer (1974)

Figure 5.2 General features of the Jemez area


36°10'52"
35°13'56"
107°00'00"
106°14'05"
VALLES CALDERA AREA
San Antonio Warm Springs
San Antonio Hot Springs
Sulphur Springs
Steam wells
Los Alamos
Spense Warm Springs
Soda Dam Springs
Jemez Hot Springs
Indian Springs
Warm Springs
San Ysidro
Cuba
La Jara
Mesa Portales
La Ventana
Cabezon
Cabezon Peak
Bernalillo Mesa
San Felipe Mesa
Jemez Canyon Reservoir
Jemez River
Santo Domingo Pueblo
San Felipe Pueblo
Santa Ana Pueblo
Cochiti Pueblo
Peña Blanca
Algodones
Angostura
El Llanito
Bernalillo
Ponderosa
Cañon
Redondo Peak
Cerros del Abrigo
Baca Location No. 1
Sandoval
0 10 20 kilometers
0 10 20 miles

By R.M. Colpitts, Jr. 6/77
After Summers, W.K. (1976)

Figure 5.3 The Jemez River Basin

Waters circulating in the hot dry rock experiment will have compositions similar to those observed in granite terrains and TDS should be well within the federal and state quality standards for potable water.

Distinguishing environmental changes created by development of the geothermal resources from changes due to natural phenomena or to other activities of man will be difficult.

Seismic effects of hydraulic fractures at the land surface are negligible. Deformation within the caldera is primairly by creep, so the seismic effects of steam production should be minimal.

Subsidence could become evident in the caldera if the pressure head in the caldera fill sediment decreases.

5.2 GEOLOGIC SETTING

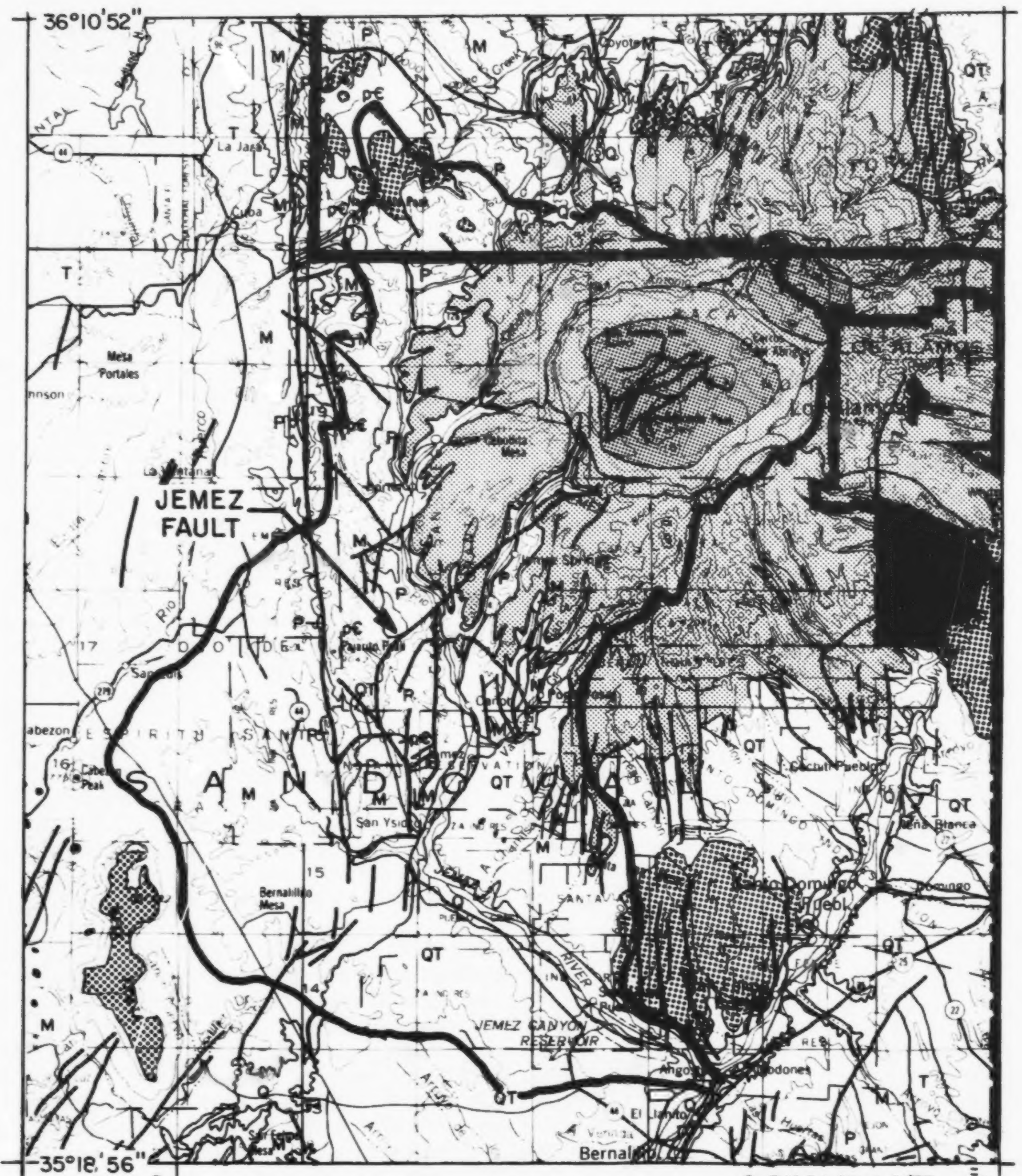
5.2.1 Topography and Drainage

The Jemez Mountains dominate the Jemez area (Figs. 5.3 and 5.4). They are a great pile of igneous rocks rising from dissected plateaus to peaks over 3,100 m (10,000 ft) above sea level. Valles Caldera lies within these towering peaks, a roughly circular depression about 19 to 24 km (12 to 15 mi) across.

The Jemez River drains Valles Caldera and empties into the Rio Grande about 10 km (6 mi) north of the community of Bernalillo. It is the only major stream draining the area of discharging thermal water in this volcanic field. All the smaller streams in the caldera area drain into the Jemez River. The Rio Chama drains the north flank of the area and the Rio Puerco drains the west flank of the Sierra Nacimiento.

The floor of the Valles Caldera lies 150 to 610 m (500 to 2,000 ft) below the caldera rim and is crumpled into numerous smaller valleys and peaks. Most of the peaks result from resurgent emplacement of rhyolite after the caldera floor collapsed. Between and below the peaks are high mountain valleys with perennial streams. San Antonio Creek drains the northern and western parts of the caldera. The East Fork of the Jemez River drains the southeastern and southern part of the caldera. Sulphur Creek and Redondo Creek drain the western interior of the caldera, including the solfataric areas where most of the drilling for steam has been concentrated.

Most of the domed mountains follow the ring fractures within the caldera wall (Kudo, 1974). Redondo Peak rises from the caldera floor inside the ring fractures to an altitude of 3,432 m (11,254 ft) and is the highest peak in the region.



36°10'52"
35°18'56"
107°00"
106°14'05"
JEMEZ FAULT
La Jara
Cuba
Mesa Portales
La Ventana
San Ysidro
Bernalillo Mesa
JEMEZ CANYON RESERVOIR
RIVER
Santo Domingo Pueblo
Cochiti Pueblo
Peña Blanca
Algodones
Bernalillo
Cabezon
Cabezon Peak
SANDOVAL
T
M
P
pЄ
QT
0
10
20 kilometers
0
10
20 miles
By R.M. Colpitts, Jr. 6/77
W.K. Summers & Assoc.
after Dane, C.H. & Bachman, G.O. (1965)

Figure 5.4 Geology of the Jemez area (legend to this figure is on following page)

EXPLANATION

Q	Quaternary
QT	Quaternary-Tertiary
T	Tertiary
M	Mesozoic
P	Paleozoic
pЄ	Pre-Cambrian
▩	Quaternary–Tertiary Basalt Flows
■	Tertiary & Cretaceous Intrusions
▨	Calderas
░	Debris field related to the Valles Caldera
╱	contact
╱	fault
╱	dike

Figure 5.4 (continued)

5.2.2 Physiography and Geomorphology

In geologic terms the Jemez Mountains are young. The oldest basalts of this complex volcanic pile appear to be of early Pliocene age with one member dated by the potassium-argon method to be at least 8.5 million years old (Kudo, 1974). Two periods of caldera formation followed these early flows, the latest about 1.1 million years ago (Kudo, 1974).

Ross, et al. (1961) describe the Jemez as "a maturely eroded, central mountainous mass surrounded by more youthfully dissected plateaus and mesas." The gentle slopes of the mesas and plateaus surrounding the Valles Caldera are deceptive, for deep canyons with steep walls cut them into numerous smaller sections. Best known of these gorges is San Diego Canyon, through which the Jemez River flows away from the caldera and south to San Ysidro where it is joined by the Rio Salado. Hot springs have built the famous Soda Dam across the Jemez River in San Diego Canyon south of the caldera. Reagan (1903) believed the series of breached travertine dams showed that San Diego Canyon was cut by the river as it continued to erode a channel through a series of uplifts.

5.2.3 Soils and Vegetation

Most of the soils in the area developed basically in place from the volcanic rocks of the pile, although the lower mesas down by Jemez Pueblo and San Ysidro contain Tertiary and Quaternary sediments of more varied composition. All but the steepest canyon walls support vegetative cover, including forests in the high plateaus and mountains. Greasewood, cacti and native grasses characterize the lower elevations with willows and cottonwoods along the rivers. Mixed conifer forests of aspen, gambel oak, pine, spruce and fir cover the higher mountains.

5.2.4 Structure

The Valles Caldera lies across the Jemez Fault (Fig. 5.4), a northeast trending fault which has been called the western margin of the Rio Grande Depression (Ross, et al. 1961). Our broader interpretation of the rift zone puts the western boundary along the Nacimiento Fault (Fig. 5.9), which trends north-south west of the Jemez Plateau and separates the Rio Grande Rift from the San Juan Basin. As Fig. 5.4 shows, numerous smaller faults criss-cross the Jemez area. Most trend north to northeast, but a few trend northwest. Many follow an en-echelon pattern similar to those associated with the rift in other areas. The Valles Caldera and the volcanic pile around the caldera cover many suspected faults.

Ross, et al. (1961) suggested that the Jemez Fault may have continued into the caldera, where the post-caldera graben aligns with the suggested extension of the Jemez Fault. Besides that graben, several radial faults break up the dome within the caldera (Smith, et al. 1970). The ring faults along which the caldera subsided have been covered by younger volcanics and alluvium, but Smith, et al. (1970) found exposures that indicate a complex fracture zone 3 to 5 km (2 to 3 mi) wide around the "moat" of the Valles Caldera.

The greater thickness of volcanics toward the east side of the Valles Caldera, compared with thickness of volcanics to the west, plus displacement along the major fault zones, led Ross, et al. (1961) to suggest that "volcanism in the Jemez Mountains is related to the initiation of faulting in the Rio Grande Depression."

5.2.5 Heat Flow

Heat flow values of about 5 HFU (1 HFU = 10^{-6} cal/cm^2/sec) occur on the west side of the caldera (Blair, et al. 1976). Reiter, et al. (1976) measured heat flows ranging from 3.8 HFU to 10.0 HFU for ten intervals in four drill holes west of the caldera, and thermal gradients ranging from 23.1°C/km to 273.8°C/km (100°F/mi to 488°F/mi) for 26 intervals in 13 holes. The wide variation among values within a hole complicates use of these data, but even the low heat flow calculated at 3.8 HFU exceeds the world average heat flow of 1.5 HFU (Blair, et al. 1976).

Reiter, et al. (1976) suggest that magmatic sources associated with the young resurgent domes in Valles Caldera could account for the unusually large heat flow of the area.

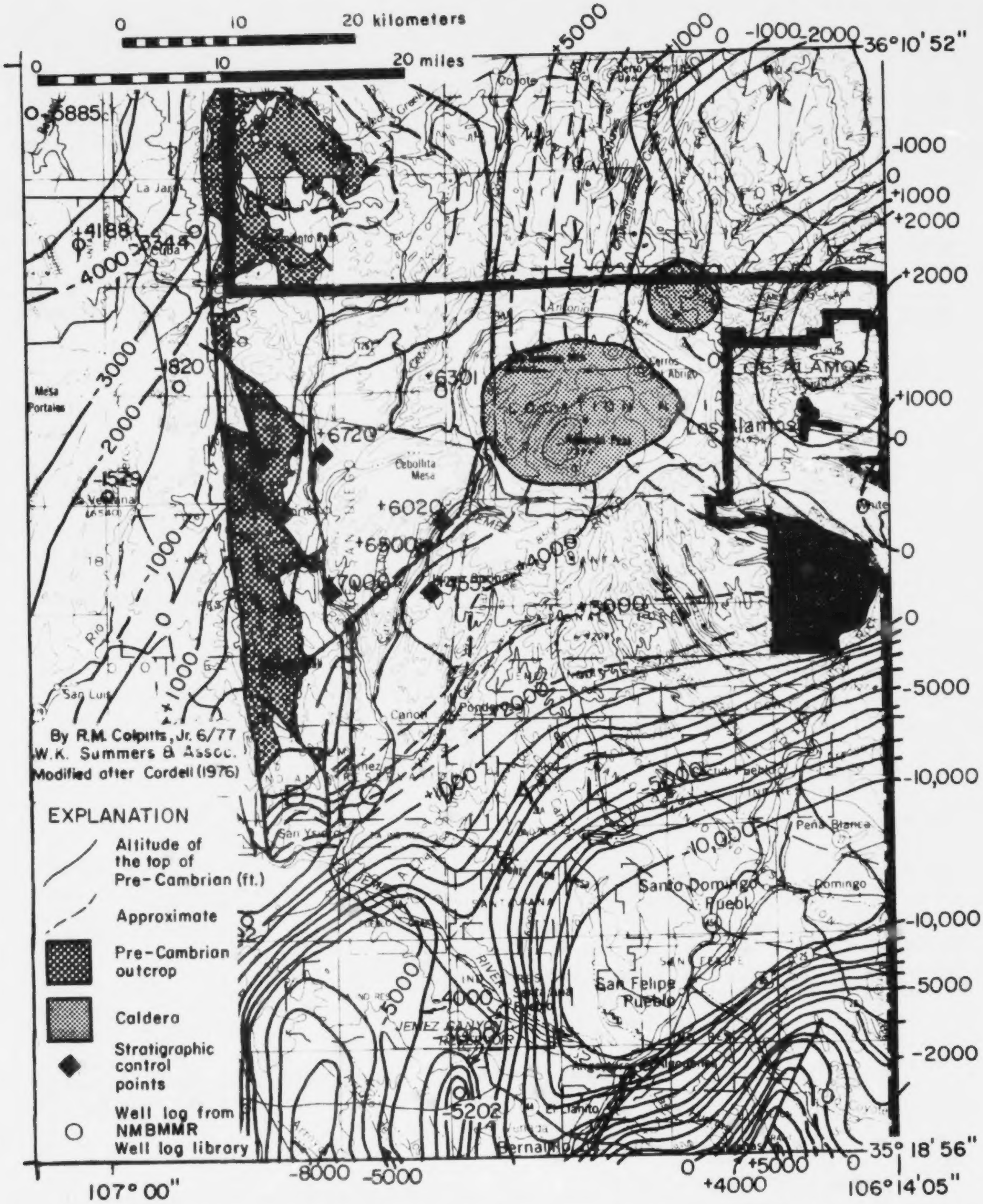
5.2.6 Stratigraphy and Paleography

Rocks of Precambrian Age--

Rocks of Precambrian age crop out in parts of the Jemez River Basin and have been found at depth in several drill holes. Fig. 5.5 shows contours on the surface of the rocks of Precambrian age. This map was modified from Cordell (1976) on the strength of additional data from the well log library of the petroleum section of the New Mexico State Bureau of Mines and Mineral Resources. Precambrian rocks in this area generally are called granite although many of them are metamorphic rocks. Tester (1974) reports granites, granodiorites, monzonites, quartz monzonites, gneisses, schists and amphibolites encountered in the Precambrian section of the granite test holes of LASL's hot dry rock project.

Rocks of Paleozoic Age

Rocks of Paleozoic age in the Jemez area are mostly sedimentary strata of Pennsylvanian and Permian age. Smith, et al. (1970) include Mississippian age rocks in their undivided Car-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-5000
-2000
-5885
+4188
-5344
-4000
-3000
-820
-2000
-1529
-1000
0
+1000
+6301
+6720
+6020
+6500
+7000
+4553
+4000
+5000
-10,000
-5000
-4000
-3000
-5202
-8000
-5000
0
+4000
+5000
0
La Jara
Cuba
Mesa Portales
Ventana Mesa
San Luis
Cebollita Mesa
Los Alamos
LOS ALAMOS
Cerros del Abrigo
Ponderosa
Canon
Jemez
San Ysidro
JEMEZ CANYON
Pena Blanca
Santo Domingo Pueblo
Domingo
San Felipe Pueblo
Algodones
Bernalillo
By R.M. Colpitts, Jr. 6/77
W.K. Summers & Assoc.
Modified after Cordell (1976)
EXPLANATION
Altitude of the top of Pre-Cambrian (ft.)
Approximate
Pre-Cambrian outcrop
Caldera
Stratigraphic control points
Well log from NMBMMR Well log library

Figure 5.5 Relief of the rocks of Precambrian age in the Jemez area

boniferous unit, but most other workers cite Magdalena Group strata of Pennyslvanian age directly overlying Madera Limestone (Purtyman, 1973). The Sandia Formation locally includes a lower limestone and upper clastic unit of sandstone, shale and limestone. The Madera Limestone contains gray shales and a few sandstones interbedded in the lower dark gray limestone, with limestone and arkosic limestone alternating with gray and red arkosic shale above it (Purtymun, 1973). Trainer (1974) found as much as 300 m (1,000 ft) of Magdalena Group rocks. Permian rocks in the area include sandstone, siltstone and shale redbeds assigned to the Abo and Yeso Formations and totalling up to 366 m (1,200 ft) (Trainer, 1974).

Rocks of Mesozoic Age--

Rocks of Mesozoic age in the Jemez River Basin include the Chinle Formation of Triassic age, the Morrison, Todilto and Entrada Formations of Jurassic age, and the Mancos Shale and Dakota Sandstone of Cretaceous age (Smith, et al. 1970). Renick (1931) measured sections of the rocks of Mesozoic age. His sections suggested a total thickness of 1,500 m (5,000 ft), but since he continually notes that these formations have highly variable thickness, that number is little better than a guess. Test holes at the LASL's hot dry rock project and some test wells in the caldera went from Abiquiu Tuff of early Tertiary age directly into Abo Formation (Purtymun, 1973). The rocks of Mesozoic age occur only in the western part of the area; over the remainder of the area they were eroded away before the rocks of early Tertiary age were deposited.

Rocks of Tertiary Age--

Renick (1931) found 250 m (820 ft) of Nacimiento Formation and 35 m (115 ft) of Wasatch Formation to be of Eocene age, and at least 460 m (1,500 ft) of Santa Fe Formation to be of Miocene to Pliocene age. These formations all consist of sedimentary rocks, mostly soft shales and sandstones of gray, tan and buff colors, although the Santa Fe commonly is red and tan. Other formation names have been used by other authors in different parts of the map area for similar sedimentary strata. Smith, et al. (1970) mapped the main caldera area, and their stratigraphic descriptions include the El Rito, Galisteo, Zia Sand and Santa Fe Formations, which contain sand, silt, clay, sandstone, shale, siltstone and conglomerate of red, tan, gray and buff colors. These rocks, of highly variable thicknesses, are interbedded with volcanic and volcanic-derived units which range from basaltic to rhyolitic in composition and also have variable thicknesses. Most of these volcanic beds belong to the Keres Group of Bailey, et al. (1969), who state that the lenticular nature of the formations in this group make its maximum actual thickness no more than 915 m (3,000 ft).

The Keres Group occurs mostly in the southern Jemez Mountains and represents a pre-caldera phase of volcanism (Kudo, 1974).

Rocks and Sediments of Quaternary-Tertiary Age--

Several pediments, terraces and older alluvium deposits, and the Polvadera Group of volcanic rocks show Pliocene to early Pleistocene ages. The Polvadera Group consists of "the sequence of basaltic, andesitic, dacitic, and rhyolitic rocks that form part of the central and most of the northern Jemez Mountains" (Bailey, et al. 1969). The lenticular nature of formations in the group allows a maximum thickness in one place of 1,070 m (3,500 ft) (Bailey, et al. 1969). Kudo (1974) points out that Santa Ana Mesa and Cerros de Rio Basalts southeast of the Jemez Mountains also erupted during the time of the Polvadera Group, and volcaniclastics accumulated between and around volcanic units.

Rocks and Sediments of Quaternary Age--

The Tewa Group volcanics represent the last stages of volcanism in the Jemez Mountains and include the famous Bandelier Tuff, the Cerro Toledo Rhyolite, the Cerro Rubio Quartz Latite, and the Valles Rhyolite (Bailey, et al. 1969). The oldest formation in the Tewa Group is the Bandelier Tuff of early Pleistocene age, and the Bandelier Tuff is divided into two members, each having a basal pumice bed overlain by ash-flow tuff (Kudo, 1974). According to Ross, et al. (1961) the Bandelier Rhyolite Tuffs

> "erupted from the crest of the Valles Range from centers now obscured, poured down valleys in the higher mountainous terrain, and spread out as broad coalescing fans on the gentler surrounding slopes... They cover an area of nearly 1,040 sq km (400 sq mi), locally attain a thickness of 300 m (1,000 ft), and represent the accumulation of more than 200 cu km (50 cu mi) of ash and pumice."

The explosive eruption of each member of this voluminous formation produced caldera collapse. The Toledo Caldera resulted from the first period of eruption of Bandelier Tuff. The Valles Caldera formed about 1.1 million years ago. The tuff from the second eruption partially obscures the Toledo Caldera (Kudo, 1974).

After each eruption, rhyolitic magmas rose along the ring fractures of the caldera and formed volcanic domes (Kudo, 1974). Within the Valles Caldera, renewed magmatic activity created the resurgent dome we call Redondo Peak (Ross, et al. 1961). Tuffaceous sediments deposited in lakes during several stages in the caldera's history lie interbedded with rhyolites of the Tewa Group (Ross, et al. 1961). Other Quaternary units include alluvium, landslike deposits, terrace gravels, fan deposits and caldera fill (Smith, et al. 1970).

5.2.7 Water Bearing Characteristics

With the exception of the rocks of Precambrian age at the site of the hot dry rock experiments, we lack detailed quantitative measurements of the water bearing or water yielding characteristics of the rocks in the Jemez area. Most of the rocks in the area are of moderate to low hydraulic conductivity and yield water to wells or springs at some place in the area, but many wells yield less than 40 lpm (10 gpm).

Water in the Precambrian basement occurs in fractures, so the concentration of fracturing controls the amount of water available from these rocks (Trainer, 1974). In the hot dry rock project on the Jemez Plateau, Purtymun, et al. (1974) found permeabilities that ranged from 5.3 x 10^{-16} sq cm (5.4 x 10^{-8} darcys), determined from water level decay over a period of months, to 1.4 x 10^{-12} sq cm (1.4 x 10^{-4} darcys) determined from pressure decay after repressurization of a hydraulic fracture, and said these permeabilities indicate the basement at the site is "dry" for project purposes.

The Paleozoic strata carry water in fractures, intergranular pores, and solution channels (Trainer, 1974 and Renick, 1931). Locally the hydraulic conductivity of these rocks could be greater than 30 m/d (100 ft/d), but the average hydraulic conductivity is undoubtedly much lower, possibly in the range of 0.03 to 0.2 m/d (0.1 to 0.5 ft/d).

The brittle sandstones and siltstones of Mesozoic age yield water to wells primarily from fractures. Tests of cores from wells elsewhere in New Mexico suggest that these brittle rocks have an interstitial hydraulic conductivity that is very low, whereas pumping tests of wells that tap fractures indicate an average hydraulic conductivity in the range of 0.3 to 2 m/d (1 to 5 ft/d).

The Tertiary valley fill tested near Los Alamos appears to have hydraulic conductivity ranging from 0.3 to 7.6 m/d (1 to 25 ft/d). Where these deposits are thick (2,070 m [6,800 ft]), they yield as much as 3,800 lpm (1,000 gpm) to wells (Purtymun and Johansen, 1974).

Quaternary sediments have the best water bearing characteristics among the rocks of the Jemez River Basin. In the high country all the materials with a granular nature, including broken rock and soil, become important water bearing units because they accept infiltrating water and transmit part of it downward (Trainer, 1974).

5.3 HYDROLOGIC SETTING

5.3.1 Introduction

The Jemez River Basin (Fig. 5.3), an area of about 2,700 sq km (1,040 sq mi), and a sub-basin of the Rio Grande Basin, contains all the thermal features of the Jemez area. It is the primary hydrologic entity that will be impacted by geothermal development. We have, therefore, concentrated our attention on the hydrology of this basin.

5.3.2 Climate

The Jemez River Basin map covers a large range of altitudes and the climate varies accordingly. The immediate area of interest around the Valles Caldera has a more restricted range of climatic variation.

Climatological Data--
Climatological data have been collected at 32 stations in the map area by the U.S. Weather Bureau. Of these, 28 have one year or more of precipitation data, 14 also have temperature and potential evapotranspiration data. LASL installed a weather station at the site of the dry hot rock project in December 1975.

Annual Means--
Annual mean precipitation at stations in the Jemez Basin ranges from 170 mm (6.73 in.) at San Ysidro, altitude 1,700 m (5,500 ft) to 634 mm (24.94 in.) at Jemez Springs, altitude 1,900 m (6,230 ft). These numbers represent the total monthly mean precipitation recorded at the stations. Fig. 5.6 shows the linear trend obtained when these mean annual precipitation data are plotted versus the altitude of the stations.

Mean annual potential evapotranspiration ranges from 544 mm (21.43 in.) at Lee Ranch, altitude 2,651 m (8,691 ft), to 1,056 mm (41.58 in.) at Pena Blanca, altitude 1,595 m (5,230 ft). Fig. 5.7 shows the linear trend obtained when annual potential evapotranspiration data are plotted versus altitude.

Mean annual deficit ranges from 93 mm (3.56 in.) at Lee Ranch, altitude 2,651 m (8,691 ft), to 873 mm (34.38 in.) at Pena Blanca, altitude 1,595 m (5,230 ft).

Mean annual surplus ranges from 0.5 mm (0.02 in.) at Bernalillo, altitude 1,539 m (5,045 ft), to 157 mm (6.20 in.) at Wolf Canyon, altitude 2,501 m (8,200 ft).

Monthy Variation During an Average Year--
Table 5.1 gives the monthly percentage of the annual total and cumulative percent of mean monthly precipitation for five

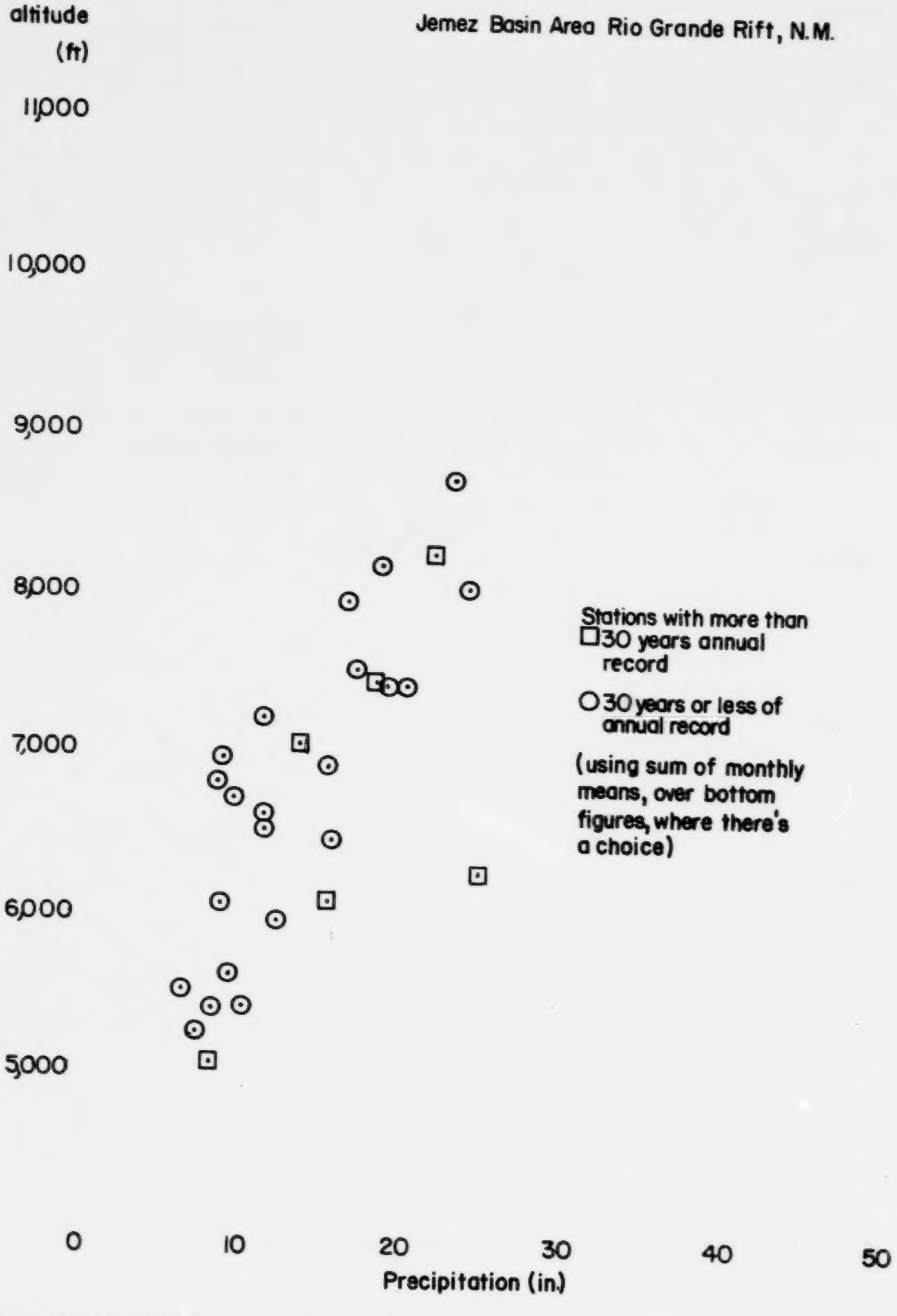


Figure 5.6 Relation of annual mean precipitation to altitude

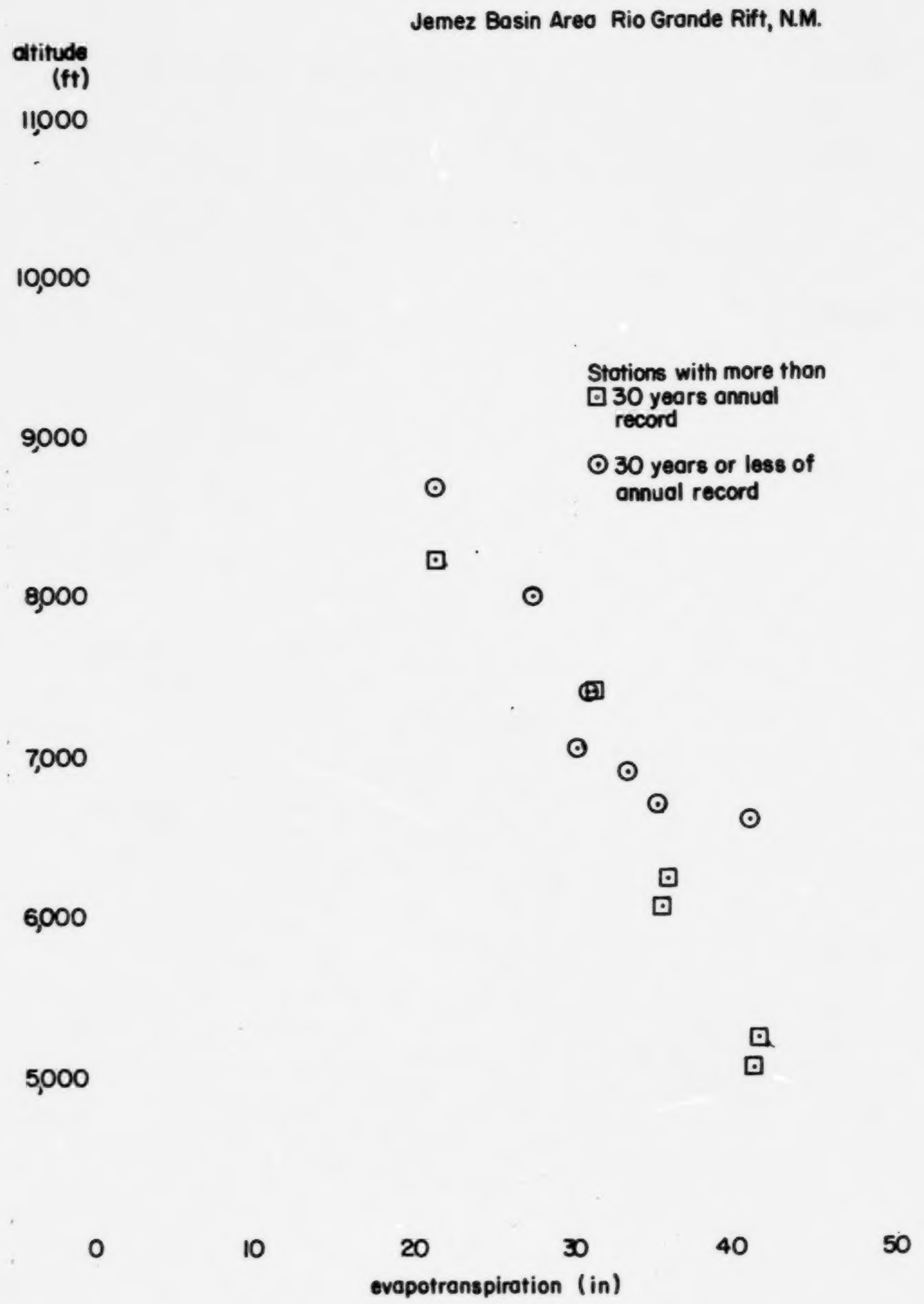


Figure 5.7 Relation of annual mean potential evapotranspiration to altitude

TABLE 5.1 CUMULATIVE PERCENT OF MEAN MONTHLY PRECIPITATION FOR STATIONS IN THE JEMEZ AREA

Station		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Lee Ranch (8691')	monthly	4.0	8.0	7.1	4.7	7.3	7.0	17.8	15.9	13.2	5.8	4.5	4.7	100.0
	cumulative	4.0	12.0	19.1	23.8	31.1	38.1	55.9	71.8	85.0	90.8	95.3	100.0	
Jemez Springs (6230')	monthly	4.9	5.4	5.9	5.8	6.7	7.1	16.3	17.4	9.9	9.7	4.6	6.1	99.8
	cumulative	4.9	10.3	16.2	22.0	28.7	35.8	52.1	69.5	79.4	89.1	93.7	99.8	
Bernalillo (5045')	monthly	4.9	4.9	6.0	5.2	6.5	4.9	15.6	17.1	13.0	11.6	4.5	5.6	99.8
	cumulative	4.9	9.8	15.8	21.0	27.5	32.4	48.0	65.1	78.1	89.7	94.2	99.8	
Pena Blanca (5230')	monthly	5.9	4.0	5.1	4.7	4.6	7.4	10.1	19.3	15.4	11.4	3.2	9.0	100.1
	cumulative	5.9	9.9	15.0	19.7	24.3	31.7	41.8	61.1	76.5	87.9	91.1	100.1	
Wolf Canyon (8220')	monthly	6.8	7.7	8.4	6.5	6.2	5.4	15.8	14.6	9.0	7.6	5.0	6.8	99.8
	cumulative	6.8	14.5	22.9	29.4	35.6	41.0	56.8	71.4	80.4	88.0	93.0	99.8	

stations in the Jemez area. The figures show a "wet" period of July, August and September over the area, followed closely by a "dry" period in November, December and January.

5.3.3 Stream Flow

The Jemez River and its tributaries are gaining, effluent streams, from the headwaters down to about the Jemez Pueblo where the river begins to flow over the Tertiary-Quaternary valley fill. From about Zia Pueblo to its confluence with the Rio Grande, the Jemez River is a losing stream. The Rio Salado, which drains the Sierra Nacimiento and the southwestern part of the Jemez River Basin, is an intermittent stream.

The USGS gages stream flow in the Jemez River Basin at four locations (Table 5.2).

Separation of the flow duration curves for the Rio Guadalupe and the Jemez River near Jemez into surface runoff and groundwater components (under the assumption that both distributions are log normal) suggests that the mean annual base flow due to groundwater discharge is about 45 and 240 lps (1.6 and 8.4 cfs) or 0.08 and 0.19 lps/sq km (0.007 and 0.017 cfs/sq mi) respectively; whereas the surface runoff is about 960 and 1,700 lps (34 and 61 cfs) or 1.59 and 1.42 lps/sq km (0.145 and 0.130 cfs/sq mi) respectively.

5.3.4 Groundwater

Flow Systems--
Local, intermediate and regional flow systems can be identified in the Jemez River Basin. The local flow systems are recharged nearby and discharge the water to springs and headwater streams such as the San Antonio Creek and Rio Cebolla. Intermediate systems underflow these local systems to discharge to the Rio Guadalupe or the Jemez River. Thus, we expect that the volume of groundwater discharging should increase downstream. This expectation is supported by the observed increase in the groundwater component estimated from the stream flow duration curves. The regional flow system involves the movement of groundwater from the recharge area within the Jemez River Basin to the Rio Grande. That such underflow occurs is difficult to prove systematically but it exists by inference. The Jemez River becomes influent near San Ysidro. Titus (1961) showed through water table contours that this water moves about due south toward the Rio Grande. Clearly any part of the groundwater underflow that had not discharged to the Jemez River must also then move toward the Rio Grande.

Recharge--
Groundwater recharge has not been quantified, but based on the apparent groundwater discharge estimated from the stream

TABLE 5.2 STREAM GAGING STATION IN THE JEMEZ RIVER BASIN

Station		Gage altitude (ft)	Drainage area (mi^2)	Years of record	Discharge	
Number	Name				Mean (cfs)	Mean/area (cfs/mi^2)
08-3215.00	Jemez River below East Fork, near Jemez Springs	6703	173	1949-1950 1951-1957 1958-	28.4	.164
08-3230.00	Rio Guadalupe at Box Canyon, near Jemez	6016	235	1958-	36.3	.154
08-3290.00	Jemez River near Jemez	5622	470	1936-1940 1949-1950 1953-	69.2	.147
08-3290.00	Jemez River below Jemez Canyon Dam	5096	1083	1936-1937 1943	54.8	.051

flow duration curves, we believe that the average recharge upon the area is larger than 0.2 lps/sq km (0.02 cfs/sq mi). Assuming 80% of the area above the gaging station on the Jemez River near Jemez Springs is recharge area, more than 6.4 mm/yr (0.25 in./yr) of the precipitation becomes recharge.

Recharge estimates can also be based on the relationship:

$$R = Pj\ (P-i)/100$$

where:

R = average annual recharge,
P = average annual precipitation,
j = a terrain constant, and
i = annual precipitation that must be exceeded for recharge to occur.

Assuming j = 0.5, i = 6, and this relationship, we see that recharge can be expected to range from about 5 mm/year (0.2 in./year) at low altitudes to about 64 mm/year (2.5 in./year) at the highest altitudes. So we have still further reason for believing that significant underflow to the Rio Grande occurs.

Discharge--
Groundwater discharge occurs to the atmosphere via evapotranspiration, to springs and streams, and as underflow to the Rio Grande. Discharge to wells within the basin serves for domestic and stock use and probably represents only a very small part of the total groundwater discharged from the basin.

5.3.5 Water Chemistry

Our knowledge of the chemical characteristics of the water of the Jemez River Basin derives from analyses of water from comparatively few sources, albeit some of these sources have been sampled many times. Detailed chemical analyses of thermal and nonthermal groundwater as well as analyses of surface water can be found in the following publications. Summers (1976) compiled the available analyses of thermal water. Kelly and Anspach (1913), Clark (1929) and Renick (1931) presented a few chemical analyses of water from nonthermal wells, springs and streams.

The LASL program has generated analyses from multiple sources (Purtymun, et al. 1974; Purtymun, et al. 1975; Purtymun, et al. 1976; and Pettitt, 1976). In addition to the LASL staff investigation, the USGS has briefly studied the water chemistry of the area (Trainer, 1974 and 1975, and Hiss, et al. 1975).

Despite these efforts the data are insufficient to predict the chemical characteristics of the groundwater at any point in the flow continuum. The data are sufficient to permit some generalizations about the chemical characteristics of the flow systems and the impact of the geothermal features on these systems.

Groundwater in the Jemez River Basin exhibits principal ion concentrations that are typical of groundwater flow in silicate rocks. Exceptions can be attributed to the concentrating effects of evapotranspiration in the discharge areas, to the presence of carbonates in the flow continuum, to the mixing of thermalwater from depths, to the reduction of hydrogen sulfide to sulfuric acid, and to exchange reactions brought on by locally higher temperatures.

Groundwater discharging from local flow systems with obviously short flow paths (e.g., wells in recharge areas, springs, and the base flow of streams in the headwater area) has the following characteristics:

1) low TDS (less than 250 mg/l),

2) relatively large ratio of silica to TDS (more than 0.25), and

3) calcium and bicarbonate ions as other principal constituents.

As the length of the flow paths increases, the TDS concentration increases, the ratio of silica to TDS decreases, and the ratios of calcium plus magnesium to the sum of all cations and bicarbonate plus carbonate to the sum of all anions (expressed as equivalents per million) decrease with increasing TDS.

For very long flow paths in silicate rocks the TDS concentration approaches that of brines and the principal ions are sodium and chloride.

Along the Rio Salado flood plain, groundwater discharges by evapotranspiration to the atmosphere so the groundwater significantly increases in dissolved solids. Gypsum and calcite precipitate, and are washed away during floods, so that the sodium and chloride ions build up; concentrations in excess of 2,000 mg/l of these ions are common. TDS in the stream flow exceed 10,000 mg/l.

The chemical characteristics of the groundwater in the Jemez River Basin above the Rio Salado depart from those expected in silicate rock terrain for several reasons. Of these perhaps the most important is the mixing of a geothermal fluid that includes carbon dioxide and hydrogen sulfide with the circulating groundwater (Trainer, 1975). At Sulphur Springs the result is a low flow acid (pH~2) spring. Elsewhere warm and hot waters generally tend to be relatively rich in silica, sodium and potassium ions because these constituents are more soluble at higher temperatures. As a result thermal waters contain these constituents in greater proportion than nonthermal waters.

In the upper Jemez River Basin the TDS of both thermal and "cool" waters range upwards from about 100 mg/l, and all the thermal waters and some of the cool waters contain silica, sodium and potassium ions in anomalous concentrations.

Some analyses of cool surface stream waters are presented in Table 5.3. These stream water analyses would be representative of cool groundwater in this area since the streams are influent at low flow. Chemical analyses of some representative thermal and cool groundwaters are presented in Table 5.5. However, the water chemistry discussions here are based on the much more extensive sample of water analyses included in the references mentioned at the beginning of this section. Therefore, some of the features or characteristics discussed may not be illustrated by these representative analyses shown in Tables 5.3 and 5.4.

On the assumption that the water obtained from the granite of Precambrian age from the LASL well GT-2 represented the thermal groundwater flowing from the caldera, Trainer estimated that the water discharging from the hot and warm springs consisted of a mixture of about one to two parts nonthermal groundwater to one part of deep thermal groundwater, whereas the two cool waters he examined showed ten to 60 parts nonthermal groundwater to one part of deep thermal groundwater.

The shortage of detailed data plus the natural mixing of thermal and nonthermal groundwater combine to make predictions of the impact of geothermal development extremely difficult.

5.4 GEOTHERMAL DEVELOPMENT

Through 1975 the Union Oil Company drilled 16 wells in the Valles Caldera, six of which produced hot water or steam with temperatures reported to be as high as 260°C (500°F). The wells range in depth from 1,830 to 2,745 m (6,000 to 9,000 ft). Stone and Mizell (1977) state that Union would need to prove 30-year production capacity from their wells to attract a 55 MW electric generating complex. However, Union Oil Company has not announced the total proven capacity of the wells, nor has the company released data on the character of the fluids.

The LASL hot dry rock experiment involves two holes, each 3,050 m (10,000 ft) deep, that are separated at the surface by about 76 m (250 ft). Water under high pressure is utilized in a

TABLE 5.3 CHEMICAL ANALYSES OF SURFACE WATERS IN THE UPPER JEMEZ RIVER BASIN (Pettit, 1976)

Location	Sulphur Creek above San Antonio Creek (F)		Jemez River below Battleship Rock (J)			San Antonio Creek above Sulphur Creek (N)			Rio Guadalupe above Jemez River (Q)		
Date of Collection (1975)	9/30	12/8	5/28	9/30	12/8	5/28	9/30	12/8	5/28	9/30	12/8
Chemical Analysis (mg/l)											
Silica (SiO_2)	32	34	33	49	53	42	51	60	17	30	27
Calcium (Ca)	26	33	13	14	14	14	22	14	23	41	50
Magnesium (Mg)	5	3	4	2	2	4	3	2	2	9	6
Sodium (Na)	15	18	7	14	15	6	15	17	11	14	16
Carbonate (CO_3)	0	0	0	0	0	0	0	0	0	4	5
Bicarbonate (HCO_3 as $CaCO_3$)	20	14	38	62	60	56	96	58	68	156	163
Sulfate (SO_4)	61	34	14	9.7	13	8.0	4.9	6.4	10	2.6	7.2
Chloride (Cl)	19	37	3	7	4	<1	3	3	<1	4	4
Fluoride (F)	0.2	0.2	0.3	0.7	0.9	0.5	1.1	1.1	0.2	0.5	0.7
Nitrate (N)	<0.1	<0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	<0.1
Total dissolved solids	184	240	98	144	144	136	194	148	152	182	176
Total hardness (as $CaCO_3$)	88	96	48	46	44	54	68	42	68	140	148
Specific conductance (μmho/cm)	260	340	140	165	180	150	190	170	140	330	340
pH	8.0	7.2	7.6	7.6	7.2	8.0	8.0	8.1	7.8	8.4	8.3
Temperature (°C)	5	0	6	9	1	6	8	0	6	13	6
Discharge estimated (l/s)	30	30	-	340	450	-	90	110	-	140	230

TABLE 5.4 CHEMICAL ANALYSES OF THERMAL WATERS IN THE UPPER JEMEZ RIVER BASIN (Pettit, 1976)

Location	San Antonio Warm Springs (RV-1)	San Antonio Hot Springs (RV-2)	Spence Spring (RV-4)		McCauley Spring (RV-5)	
Date of Collection (1975)	8/14[b]	8/12	9/24[c]	12/9	9/24[d]	12/9
Chemical Analysis (mg/l):						
Silica (SiO_2)	97	83	65	68	53	59
Calcium (Ca)	6	6	7	7	10	10
Magnesium (Mg)	<1	<1	2	2	4	5
Sodium (Na)	27	22	49	49	19	20
Carbonate (CO_3)	0	0	0	0	0	0
Bicarbonate (HCO_3 as $CaCO_3$)	58	56	120	128	76	74
Sulfate (SO_4)	10	7.0	15	16	3.5	5.0
Chloride (Cl)	6	14	8	10	4	4
Fluoride (F)	1.3	0.9	0.6	0.7	0.8	1.0
Nitrate (N)	0.8	0.3	<0.1	0.1	0.3	<0.1
Total dissolved solids	244	166	242	258	154	148
Total hardness (as $CaCO_3$)	18	16	26	28	40	44
Specific conductance (μmhos/cm)	120	195	290	280	170	170
pH	7.6	7.5	8.0	8.3	7.9	8.0
Temperature (°C)	38	41	41	40	32	30

---

[b] Collected R. L. Borton, SEO, flow 0.6 ℓ/s.

[c] Collected R. L. Borton, SEO, flow 1.0 ℓ/s.

[d] Collected R. L. Borton, SEO.

process known as hydraulic fracturing to create cracks in hot granite (otherwise, it has a very low hydraulic conductivity). The fractures serve two purposes:

1) they provide communication between the wells, and

2) they expose a large heat-exchange surface of rock with a temperature of 204°C (400°F). In a 20-hour experiment in early June 1977 cold water was pumped down one hole at 60 to 70 bars (900 to 1,000 psi). It circulated through the crack system, was heated, and flowed into the second hole. Water discharged from the second hole at temperatures of 129°C (265°F).

Thus for the Jemez area the impact of two distinctly different efforts must be assayed. Information about the conventional field is remarkably sparse. LASL, on the other hand, has made extensive studies and has gathered extensive data for the purpose of appraising environmental impacts.

Fig. 5.8 is a simplified cross section through the caldera that shows the relationship of the salient features of the area. We have inferred the water table, but its shape must be essentially as shown or the streams at higher altitudes would not be gaining streams. The shape of the water table near the Rio Grande derives from a map by Purtymun and Johansen (1974).

The flow of groundwater in the Jemez River Basin (as well as the groundwater flow in the Puerco Basin and the Rio Grande Basin generally) is southerly (i.e., normal to the plane of the section in Fig. 5.8). Thus a comparison of this section of the map with the geologic map (Fig. 5.4) and the location of thermal features (Fig. 5.3) suggests that the thermal fluids are all derived from the Valles Caldera. The high heat flow on the west is not so much due to more heat on the west side, but to the greater thickness of groundwater bearing rocks on the east, so that the heat is swept away by the large influx of groundwater. The lack of heat indication on the north edge of the caldera is probably due in part to the sweep of the groundwater flow system that carries the heat via mass transfer from north to south.

For the most part the discharging heat is carried in water that underflows the local and intermediate flow systems, surfacing only at windows in the local flow systems.

The moderately warm springs near the confluence of the Rio Salado and the Jemez River may indeed be the discharge region for the intermediate flow that underflows the Rio Guadalupe local flow systems.

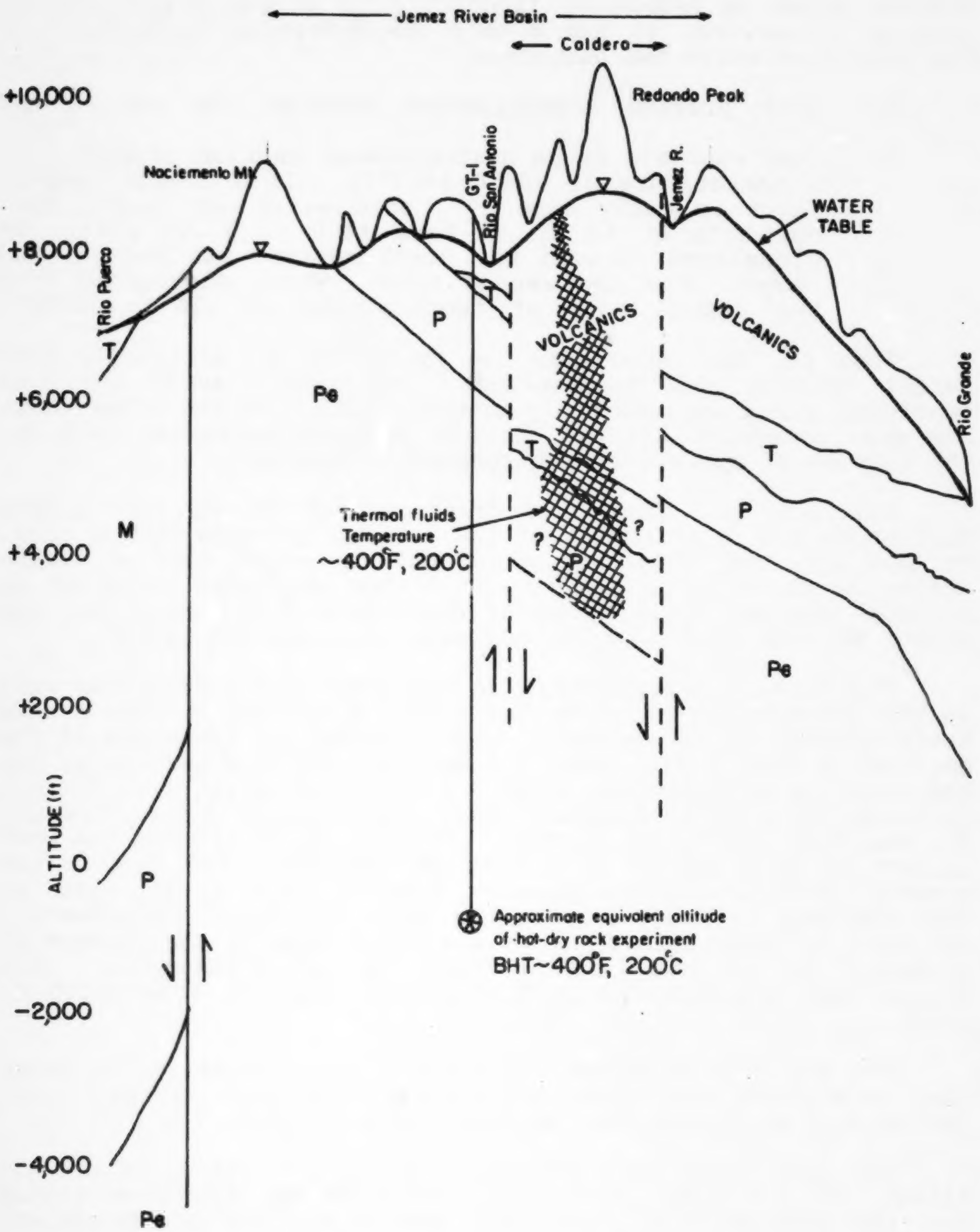

Jemez River Basin
Caldera
+10,000
Redondo Peak
Nacimiento Mt
GT-I
Rio San Antonio
Jemez R.
WATER TABLE
+8,000
Rio Puerco
T
P
T
VOLCANICS
VOLCANICS
+6,000
Pe
T
T
Rio Grande
Thermal fluids Temperature
~400°F, 200°C
M
+4,000
?
P
?
P
Pe
+2,000
ALTITUDE (ft)
0
P
Approximate equivalent altitude of hot-dry rock experiment
BHT~400°F, 200°C
-2,000
-4,000
Pe

Figure 5.8 Simplified cross section through the Valles Caldera and GT-1. The surface trace of the section is perpendicular to the Rio Grande.

5.5 WATER POLLUTION POTENTIAL

5.5.1 Caldera Area

Only two partial analyses of water from test wells in the caldera are available. These analyses are of the steam condensates from one of the early test wells drilled near Sulphur Springs. These analyses both show 24 mg/l fluoride but relatively low dissolved solids (2,970 and 1,700 mg/l).

The water of the hot springs in the Jemez area generally contains more than 2 mg/l fluoride and more than 4 mg/l boron. Spectrographic analyses of the water from Soda Dam Hot Springs and Jemez Spring indicate arsenic concentrations ranging from 0.3 to 13 mg/l. We conclude, therefore, that fluoride, boron and arsenic concentrations in the effluent from the steam wells are likely to be potential pollutants in this area.

The TDS concentration of the thermal waters of the Jemez area are almost all less than 10,000 mg/l and generally less than than 4,000 mg/l.

Throughout the area hydrogen sulfide and carbon dioxide discharge with the thermal waters. The hydrogen sulfide could oxidize to sulfuric acid and pose a gas and liquid emission problem.

5.5.2 Hot Dry Rock Experiment

Presumably, the native water in the granite will be similar to the water in the caldera, but since the program calls for the circulation of "cool" water from the surface through the fractured rocks, the native water should not pose a problem. However, the circulating water should react with the hot rock and increase its TDS content.

According to Pettitt (1976),

> "The mineral composition of the granite comprising the downhole reservoir contains mostly iron, potassium, sodium, calcium and magnesium as hydrated oxides of aluminum and silica, pure quartz, and some carbonates. Dissolved material brought to the surface will resemble the products of the natural weathering of granite, and should not be objectionable. An important part of the program is directed toward controlling the dissolution and reprecipitation of such minerals. Present estimates indicate a total dissolved solids content of less than 500 ppm for fluids circulating in a 200°C (392°F) reservoir with dissolved silica (SiO_2) as the major component."

5.6 SEISMICITY

Historic seismicity and seismic risk along the Rio Grande Rift and in the Jemez Valles Caldera region in general are discussed in Geonomics (in press). LASL seismologists have studied the seismic characteristics of the Fenton Hill site (and hence of the surrounding area) since 1973 and results from this program are discussed below.

Fig. 5.9 shows the locations of microearthquake epicenters in north-central New Mexico, September 1973 through December 1975. This map shows a lower rate of occurrence of microearthquakes around the Fenton Hill site. According to Pettitt (1976):

> "An estimate of seismic risk from natural events can be made from the microearthquake recording carried out since September 1973. Because of the moderate levels and sporadic nature of earthquake activity in New Mexico, one must exercise caution in extrapolating the results to too small an area or too long a time interval. Fig. [5.10] shows a plot of cumulative number versus magnitude for all earthquakes detected since September 1, 1973 within 225 km (140 mi) of Los Alamos (an included area of 160,000 sq km [61,500 sq mi]). An extrapolation of these data using the fitting b = 0.77 slope projects the maximum probable earthquake for this area per century to be a magnitude 6.6 event. Because the slopes of such curves may be biased by observational selection effects, giving rise to incomplete coverage of the smaller events, some investigators prefer to impose the slope constraint of b = 1.0 on the data. When this is done, the present seismicity rates correspond to a maximum probable earthquake per century with a local magnitude of 5.6, in close agreement with similar instrumental studies of other parts of the state. The 5.6 local magnitude projection is, however, somewhat smaller than projections (~6.0) made on the basis of historical damage reports.
>
> Although considerable caution must be exercised when making long-term projections for areas much smaller than that considered above, the observed distribution of seismicity in the Jemez region indicates that local magnitude >1 earthquakes are almost completely absent from the central part of the Jemez Mountains. The explanation of this phenomenon is probably the

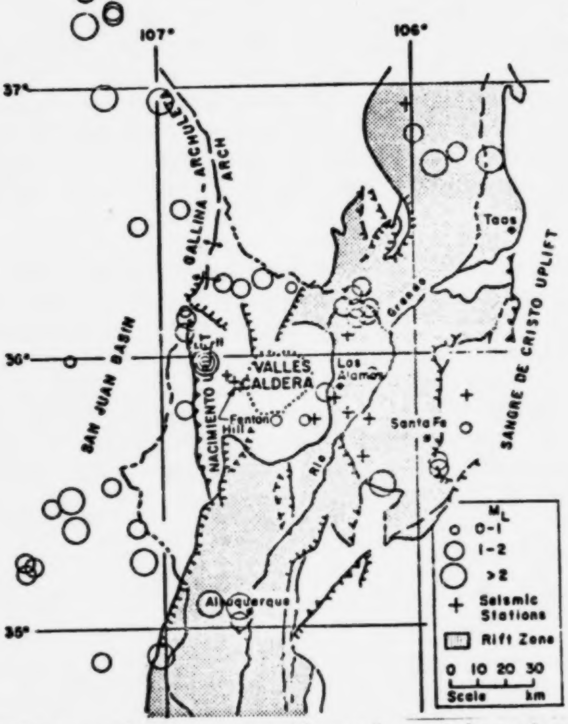

107°
106°
37°
36°
35°
GALLINA - ARCHULETA ARCH
SAN JUAN BASIN
NACIMIENTO UPLIFT
VALLES CALDERA
Fenton Hill
Los Alamos
Santa Fe
Taos
Albuquerque
Rio Grande
SANGRE DE CRISTO UPLIFT
M_L
0-1
1-2
>2
Seismic Stations
Rift Zone
0 10 20 30
Scale km

Figure 5.9 Locations of microearthquake epicenters in north-central New Mexico, September 1973-December 1975

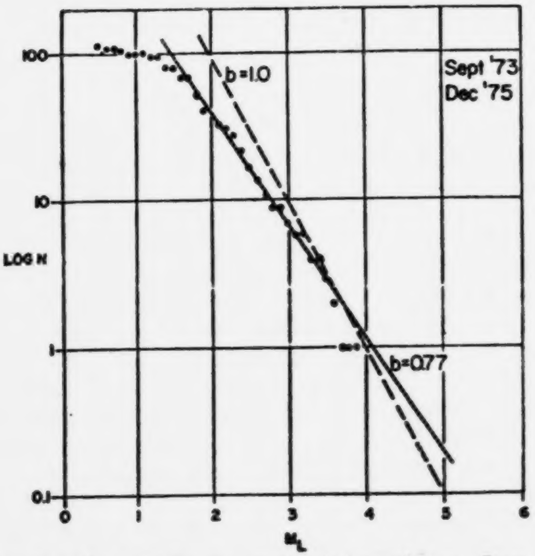


Figure 5.10 Magnitude-frequency relationship for all earthquakes within 225 km of Los Alamos, September 1973-December 1975

> same as that proposed for a similar situation in the Yellowstone Caldera complex: that strain energy at shallow depths is being relieved by creep rather than by brittle failures. This interpretation is supported by data on tectonic and geologic structure, historical earthquake records, and other geophysical evidence including gravity, aeromagnetic, and high heat flow data."

The on-site seismographs have operated throughout LASL's hydraulic fracturing experiment, and according to Pettitt (1976), no surface seismic activity associated with the fracturing experiment has been detected by the equipment, but analysis of downhole signals associated with the hydraulic fracturing shows that these nanoearthquakes have magnitudes of -6 to -3. More than two years of monitoring microearthquakes by LASL seismologists has led them to the conclusion that the Nacimiento Fault System is a seat of continuing but moderate activity.

5.7 SUBSIDENCE

We can only speculate about the subsidence potential in the Jemez area. At the hot dry rock site the rocks have sufficient strength to preclude subsidence. Within the caldera, however, sedimentary fill may compact if the pressure head is reduced. Presently no data are available to the public which would allow estimates of the magnitude of this potential problem.

5.8 CONCLUSION

The subsurface environmental impact of geothermal development in the Jemez area will be restricted to the effects of effluent disposal. One well in the caldera system was drilled as a reinjection well (Summers, 1976). If the waste effluent from field development is indeed injected into the well, the impact of the effluent will be negligible except when the producing wells are free flowed during their drilling and production. The effect of the discharge will depend in large part on the state of the Jemez River Basin at the time of discharge. If the basin discharges flood water from spring runoff or summer storms, the concentration of offensive components in the discharging effluent would not be detectable. However, at low base flow the concentrations of arsenic, boron and fluoride in the effluent could raise the concentrations in the Jemez River to levels that exceed present state and federal standards.

REFERENCES

Bailey, R. A., R. L. Smith and C. S. Ross. Stratigraphic Nomenclature of Volcanic Rocks in the Jemez Mountains, New Mexico. USGS Bull. 1274-P, 19 p., 1969.

Blair, A. G., J. W. Tester and J. J. Mortensen. LASL Hot-dry-rock Geothermal Project, July 1, 1975-June 30, 1976. Los Alamos Scientific Laboratory, LA-6525-PR, 238 p.

Clark, J. D. The Saline Springs of the Rio Salado, Sandoval County, New Mexico. University of New Mexico, Bull. 163, Chem. Ser., v. 1, No. 3, 1929.

Cordell, Lindrith. Aeromagnetic and Gravity Studies of the Rio Grande Graben in New Mexico Between Belen and Pilar. New Mexico Geol. Soc., Spec. Pub. No. 6, p. 62-70, 1976.

Dane, C. H. and G. O. Bachman. Geologic Map of New Mexico. USGS, scale 1:500,000, 2 sheets, 1965.

Geonomics, Inc. Baseline Geotechnical Data for Four Geothermal Areas in the United States. EPA, Environmental Monitoring and Support Laboratory, Las Vegas, Nevada, in press.

Hiss, W. L., F. W. Trainer, B. A. Black and D. R. Posson. Chemical Quality of Ground Water in the Northern Part of the Albuquerque-Belen Basin, Bernalillo and Sandoval Counties, New Mexico. New Mexico Geol. Soc., Guidebook 26th Field Conf., p. 219-235, 1975.

Kelly, C. and E. V. Anspach. A Preliminary Study of Waters of the Jemez Plateau, New Mexico. University of New Mexico, Bull., Chem. Ser., v. 1, No. 1, 1913.

Kudo, A. M. Outline of the Igneous Geology of Jemez Mountains Volcanic Field. New Mexico Geol. Soc., Guidebook 25th Field Conf., p. 287-289, 1974.

Pettitt, R. A. Environmental Monitoring for the Hot Dry Rock Geothermal Energy Development Project, Annual Report for the Period of July 1975-June 1976. Los Alamos Scientific Laboratory, LA-6504-SR, 92 p., 1976.

Purtymun, W. D. Geology of the Jemez Plateau West of Valles Caldera. Los Alamos Scientific Laboratory, LA-5124-MS, 13 p., 1973.

Purtymun, W. D. and S. Johansen. General Geohydrology of the Pajarito Plateau. New Mexico Geol. Soc., Guidebook 25th Field Conf., p. 347-349, 1974.

Purtymun, W. D., F. G. West and W. H. Adams. Preliminary Study of the Quality of Water in the Drainage Area of the Jemez River and Rio Guadalupe. Los Alamos Scientific Laboratory, LA-5595-MS, 26 p., 1974.

Purtymun, W. D., W. H. Adams and J. W. Owens. Water Quality in Vicinity of Fenton Hill Site, 1974. Los Alamos Scientific Laboratory, LA-6093, 1975.

Purtymun, W. D., W. H. Adams, A. K. Stoker and F. G. West. Water Quality in Vicinity of Fenton Hill Site, 1974. Los Alamos Scientific Laboratory, 1976.

Reagan, A. B. Geology of the Jemez-Albuquerque Region, New Mexico. Am. Geologist, v. 31, No. 21, p. 67-111, 1903.

Reiter, M., C. Weidman, C. L. Edwards and H. Hartman. Subsurface Temperature Data in Jemez Mountains, New Mexico. New Mexico Bureau of Mines and Mineral Resources Circ. 151, 16 p., 1976.

Renick, B. C. Geology and Ground Water Resources of Western Sandoval County, New Mexico. USGS Water Supply Paper 620, 117 p., 1931.

Ross, C. S., R. L. Smith and R. A. Bailey. Outline of the Geology of the Jemez Mountains, New Mexico. New Mexico Geol. Soc., Guidebook 12th Field Conf., p. 139-143, 1961.

Smith, R. L., R. A. Bailey and C. S. Ross. Geologic Map of the Jemez Mountains, New Mexico. USGS Map I-571, 1970.

Stone, W. J. and N. B. Mizell. Geothermal Resources of New Mexico a Survey of Work to Data. New Mexico Bureau of Mines and Mineral Resources Open File Report 73, 117 p., 1977

Summers, W. K. Catalog of Thermal Waters in New Mexico. New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 4, 80 p., 1976.

Tester, J. W. Proceedings of the NATO-CCMS Information Meeting on Dry-hot-rock Geothermal Energy. Los Alamos Scientific Laboratory, LA-5818-C, NATO CCMS Report No. 38, 40 p., 1974.

Titus, F. B., Jr. Ground Water Geology of the Rio Grande Trough in North-central New Mexico, with Sections on the Jemez Caldera and the Lucero Uplift. New Mexico Geol. Soc., Guidebook 12th Field Conf., p. 186-192, 1961.

Trainer, F. W. Ground Water in the South-western Part of the Jemez Mountains Volcanic Region, New Mexico. New Mexico Geol. Soc., Guidebook 25th Field Conf., p. 337-345, 1974.

Trainer, F. W. Mixing of Thermal and Nonthermal Waters in the Margin of the Rio Grande Rift, Jemez Mountains, New Mexico. New Mexico Geol. Soc., Guidebook 26th Field Conf., p. 213-218, 1975.

Tuan, Yi-Fu, C. E. Everard and J. G. Widdisor. The Climate of New Mexico. New Mexico State Planning Office, Santa Fe, New Mexico, 169 p., 1969.

APPENDIX A

ABBREVIATIONS AND CHEMICAL SYMBOLS

ABBREVIATIONS

acre-ft --acre-feet
APCD --Air Pollution Control District
ARB --California Air Resources Board
atm --atmosphere
BTU --British Thermal Unit
°C --degrees Celcius
cal --calorie
Cal Tech --California Institute of Technology
cfs --cubic feet per second
cm --centimeter
cu --cubic
d --day
ERDA --U.S. Energy Research and Development Administration
EPA -U.S. Environmental Protection Agency
emp --equivalence per million
EPRI --Electric Power Research Institute
°F --degrees Fahrenheit
ft --feet
g --acceleration of gravity
g --grams
gpd --gallons per day
gpm --gallons per minute
ha --hectare
ha-m --hectare-meter
HFU --heat flow unit
hr --hour
in. --inch
J --joule
JTU --Jackson turbidity unit
KGRA --Known Geothermal Resource Area
kg --kilogram
kH --transmissivity
km --kilometer
kW --kilowatt
kW.hr --kilowatt-hour
LASL --Los Alamos Scientific Laboratory
l --liter
lb --pound

ABBREVIATIONS (continued)

lpd --liter per day
lpm --liter per minute
lps --liter per second
lsd --land-surface datum
m --meter
M --Richter magnitude
MM --Modified Mercalli intensity
md --millidarcy
md-ft --millidarcy-feet
mg --milligram
mg/l --milligram per liter
mgal --milligal
mm --millimeter
msl --mean sea level
mV --millivolt
MW --megawatt
MWe --megawatt (electricity)
NCPA --Northern California Power Administration
NCER --National Center for Earthquake Research
NIDWR --National Interim Drinking Water Regulations
ohm-m --ohm-meter
OIT --Oregon Institute of Technology
oz --ounce
pCi/l --picocurie per liter
PG&E --Pacific Gas and Electric Company
ppm --parts per million
psi --pounds per square inch
psia --pounds per square inch absolute
psig --pounds per square inch gage
SDG&E --San Diego Gas and Electric
sec --second
sq --square
TDS --total dissolved solids
U.C.B. --University of California, Berkeley
USBR --U. S. Bureau of Reclamation
USDA --U. S. Department of Agriculture
USGS --U.S. Geological Survey
USPHS --U.S. Public Health Service
U.C.R. --University of California, Riverside
μmho/cm --micro mho per centimeter
ρ --density
ϕch --specific capacitance

CHEMICAL SYMBOLS

Ac --Actinium
Al --Aluminum
Am --Americium
Cd --Cadmium
Ca --Calcium
Cf --Californium

CHEMICAL SYMBOLS (continued)

Sb	--Antimony	C	--Carbon
Ar	--Argon	Ce	--Cerium
As	--Arsenic	Cs	--Cesium
At	--Astatine	Cl	--Chlorine
Ba	--Barium	Cr	--Chromium
Bk	--Berkelium	Co	--Cobalt
Be	--Beryllium	Cu	--Copper
Bi	--Bismuth	Cm	--Curium
B	--Boron	Dy	--Dysprosium
Br	--Bromine	Es	--Einsteinium
Er	--Erbium	P	--Phosphorus
Eu	--Europium	Pt	--Platinum
Fm	--Fermium	Pu	--Plutonium
F	--Fluorine	Po	--Polonium
Fr	--Francium	K	--Potassium
Gd	--Gadolinium	Pr	--Praeseodymium
Ga	--Gallium	Pm	--Promethium
Ge	--Germanium	Pa	--Protactinium
Au	--Gold	Ra	--Radium
Hf	--Hafnium	Rn	--Radon
He	--Helium	Re	--Rhenium
Ho	--Holmium	Rh	--Rhodium
H	--Hydrogen	Rb	--Rubidium
In	--Indium	Ru	--Ruthenium
I	--Iodine	Sm	--Samarium
Ir	--Iridium	Sc	--Scandium
Fe	--Iron	Se	--Selenium
Kr	--Krypton	Si	--Silicon
La	--Lanthanum	Ag	--Silver
Lr	--Lawrencium	Na	--Sodium
Pb	--Lead	Sr	--Strontium
Li	--Lithium	S	--Sulfur
Lu	--Lutetium	Ta	--Tantalum
Mg	--Magnesium	Tc	--Technitium
Mn	--Manganese	Te	--Tellurium
Md	--Mendelevium	Tb	--Terbium
Hg	--Mercury	Tl	--Thallium
Mo	--Molybdenum	Th	--Thorium
Nd	--Neodymium	Tm	--Thulium
Ne	--Neon	Sn	--Tin
Np	--Neptunium	Ti	--Titanium
Ni	--Nickel	W	--Tungsten
Nb	--Niobium (Columbium)	U	--Uranium
		V	--Vanadium
N	--Nitrogen	Xe	--Xenon
No	--Nobelium	Yb	--Ytterbium
Os	--Osmium	Y	--Yttrium

CHEMICAL SYMBOLS (continued)

O --Oxygen
Pd --Palladium
Zn --Zinc
Zr --Zirconium

NH_3 --Ammonia
NH_4^+ --Ammonium
HCO_3^- --Bicarbonate
H_3BO_3 --Boric Acid
$CaCO_3$ --Calcium Carbonate
CO_2 --Carbon Dioxide
CO --Carbon Monoxide
CO_3^{-2} --Carbonate
C_2H_6 --Ethane
H_2 --Hydrogen
HF --Hydrogen Fluoride
H_2S --Hydrogen Sulfide
CH_4 --Methane
NO_3^- --Nitrate
NO_2- --Nitrite
N_2 --Nitrogen
O_2 --Oxygen
PO_4^{-3} --Phosphate
H_3PO_4 --(Ortho) Phosphoric Acid
SiO_2 --Silica Dioxide
NaCl --Sodium Chloride
SO_4^{-2} --Sulfate
SO_2 --Sulfur Dioxide

APPENDIX B

EXPLANATION FOR DESCRIPTION OF WELLS TABLES

Map Number: Number on maps in this report.

State Number: The wells are identified according to their location in the rectangular system for the subdivision of public land. The identification consists of the township number, north or south; the range number, east or west; and the section number. The section is further subdivided into sixteen 40-acre tracts lettered consecutively (excepting I and O), beginning with A in the northeast corner of the section and progressing in a sinusoidal manner to R in the southeast corner. Wells within the 40-acre tract are numbered sequentially.

Owner or Name: The apparent owner or user. In some cases, the local name of the well is given.

Ownership:

F	Federal Government
N	Corporation or company, churches, lodges and other non-profit, nongovernment groups
P	Private
S	State agency
W	Water district

Water Use:

G	Geothermal
H	Domestic
N	Industrial, including mining
R	Recreation
U	Unused
Z	Other

Well Use:

H	Heat reservoir
O	Observation
P	Oil or gas
R	Recharge
T	Test hole
U	Unused or abandoned
W	Withdraw water
Z	Destroyed

Diameter: Inside diameter of the well, in inches; nominal inside diameter, in inches, of the innermost casing at the surface for drilled cased wells.

Deepest Depth: Depth, in feet below land-surface datum, of drilled hole.

Depth Cased: Length of casing, in feet below land-surface datum or to the top of the perforated or screened interval.

Depth of Well: Depth, in feet below land-surface datum, is defined as the bottom of the perforated or screened interval or the drilled depth.

Altitude of lsd: Altitude of land-surface datum, in feet, above or below (-) mean sea level. Land-surface datum is an arbitrary plane closely approximating land surface at the time of the first measurement and used as the plane of reference for all subsequent measurements.

Water Level: Depth to water, in feet, above (+) or below land-surface datum:
F Flows, head unknown
D Dry

Date Measured: Month and year of the water level measurement.

Yield of Well: In gallons per minute.

APPENDIX C

U.S.-METRIC CONVERSION TABLE

U.S. CUSTOMARY	U.S. EQUIVALENT	METRIC EQUIVALENT
	Length	
inch (in)	0.083 ft	25.4 millimeters (mm)
inch	0.083 ft	2.54 centimeters (cm)
foot (ft)	0.33 yd, 12 in	0.3048 meter (m)
yard (yd)	3 ft, 36 in	0.9144 m
mile (mi)	5,280 ft, 1,760 yd	1.609 kilometer (km)
	Area	
square foot (sq ft)	144 in	0.0929 sq m
square yard (sq yd)	1,294 sq in, 9 sq ft	0.836 sq m
acre	43,560 sq ft, 4,840 sq yd	4,047 sq m
acre	43,560 sq ft, 4,840 sq yd	0.4046 hectare (ha)
square mile (sq mi)	640 acres	2.59 sq km
	Volume	
gallon	4 quarts	3.785 liters (l)
acre-foot (acre-ft)	325,850.28 gallons	0.12335 hectare-meter (ha-m)
acre-foot/acre		0.3048 ha-m
cubic feet (cu ft)		0.02832 cubic meter (cu m)
cubic mile (cu mi)		4.1655 cu km
	Flow Rate	
gallons per second		3.785 liters per second (lps)
gallons per minute (gpm)		3.785 liters per minute (lpm)
gallons per day (gpd)		3.785 liters per day (lpd)
gallons per minute/foot (gpm/ft)		12.418 lpm/m
gallons per day/ft (gpd/ft)		12.418 lpd/m
18.2 gpd/sq ft @ 60°F		9.66×10^{-4} cm/sec @ 20°C
pounds per hour		1.262×10^{-4} kg/sec
cu ft per sec (cfs)		28.32 lps

APPENDIX C. (continued)

U.S. CUSTOMARY	U.S. EQUIVALENT	METRIC EQUIVALENT
	Miscellaneous	
°F		9/5(°C) + 32
1.12°F/mi		1°C/km
1°F/mi		0.8939°C/km
°C		(°F - 32)(5/9)
pounds per square inch (psi)		0.7031 g/sq cm
pounds per square inch (psi)		0.0689 bar
British Thermal Unit (BTU)		1,055 joules (J)
BTU/lb		2,325.84 J/kg
ounce		28.35 g
pound		0.4536 kg
ton		0.907 metric ton

APPENDIX D

GLOSSARY

alluvium: Relatively unconsolidated detrital material (clay, silt, sand, gravel) deposited in comparatively recent geologic time by flowing water.

aquiclude: Relatively impermeable strata that absorbs water slowly and functions as a boundary of an aquifer. It does not transmit groundwater quickly enough to supply a well or spring. Clay or shale beds and faults often act as aquicludes.

aquifer: A body of rock or sediment that contains sufficient saturated permeable materials to conduct groundwater and yield significant quantities of groundwater to wells and springs.

aquitard: Confining strata that retards the flow of water, but does not prevent flow to or from an adjacent aquifer.

artesian water: Groundwater confined under hydrostatic pressure. Water in an artesian well rises above the level of the water table under artesian pressure, but does not necessarily reach the land surface. The term is sometimes restricted to mean only a flowing artesian well.

Bouguer anomaly: A gravity value calculated by allowing for the attraction effect of topography, but not for that of isostatic compensation.

brine: A solution containing more than 3.5% total dissolved solids (35,000 mg/l). This is the approximate TDS of seawater.

caprock (geothermal): A relatively impermeable rock layer overlying a hot water or steam reservoir which prevents the heat or fluid from directly migrating or dissipating upward to the surface.

clast: A rock fragment produced by mechanical weathering (disintegration) of a larger rock mass.

conductive heat flow: Heat transfer from a higher temperature to a lower temperature region by molecular impact (vibration) without transfer of matter itself.

convective heat flow: Mass transfer of heat due to temperature-caused density gradients, e.g., circulation of hot water in a convecting geothermal reservoir.

connate water: Water trapped, at the time of deposition, in the interstices of a sedimentary or extrusive igneous rock.

contour line: A line that passes through all consecutive points of equal value for a parameter which is variable, e.g., topographic elevation, groundwater level, or temperature.

craton: A part of the earth's crust which has attained stability, and which has been little deformed for a prolonged period.

deuterium: The hydrogen isotope that occurs in water and has twice the mass of ordinary hydrogen. It is also called heavy hydrogen and its chemical symbol is "D".

diktytaxitic: Rock texture of some olivine basalts in the Pacific northwest, characterized by numerous jagged, irregular vesicles bounded by crystals.

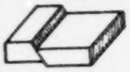
effluent: Flowing forth or out, emanating: a) a surface stream that flows out of a lake or larger stream, b) a liquid discharged as waste.

electrical resistivity survey: A geophysical exploration technique where electric current is artificially introduced into the ground and the distribution of current below the surface is measured by electrodes separated by increasing increments. Depths to geologic interfaces may be determined by plotting apparent resistivity versus electrode separation.

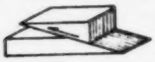
eutrophication: The artificial or natural enrichment of a lake by an influx of nutrients required for the growth of aquatic plants.

fault: A surface or zone of rock fracture along which there has been displacement, from a few centimenters to hundreds of kilometers in scale. Faults are classified according to the relative motion of the rock on each side of the fracture zone, or fault plane. These classifications are illustrated below in the diagrams of fault types.

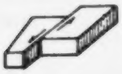
NORMAL



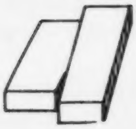
REVERSE



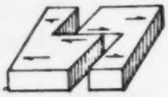
STRIKE - SLIP



ROTATIONAL



TRANSFORM



fault scarp: A fairly steep slope or cliff formed directly by movement along one side of a fault and representing the exposed surface of the fault plane before modification by erosion and weathering.

fumarole: A volcanic vent from which gases and vapors are emitted; it is characteristic of a late stage of volcanic activity.

geomorphology: The science of the earth's surface; specifically the classification, description, origin, and development of present land forms and their relationships to underlying structures.

geosyncline (variety eugeosyncline, miogeosyncline): Often an elongate crustal depression or basin, often subsiding, where thousands of meters of sediment accumulate, usually in some phase of a marine environment.

geothermal gradient (temperature gradient): The rate of increase of temperature in the earth with depth. The average gradient is approximately 1°C per 30 m (2°F per 100 ft).

geothermal water: "Strictly defined, any spring, [ground] or well water whose average temperature is noticeably above the mean annual temperature of the air at the same locality may be classed as thermal. Among European springs that are developed commercially, only those whose temperature is higher than about 20°C (68°F) are classed as thermal. In the United States, only those springs are called thermal whose temperature is at least 8°C (15°F) above the mean annual temperature of the air at their localities. In areas where the mean annual air temperature is low, some springs that do not freeze in winter because of natural protective conditions are considered to be thermal; in tropical areas some springs that are only a few degrees warmer than the temperature of the air may be considered thermal." (Thermal Springs of the United States and Other Countries of the World--a Summary, G. A. Waring, USGS Prof. Paper 492, 1965). The definition used for Imperial Valley geothermal water is somewhat different--see section 2.3.

geothermometry (geologic thermometry): 1) The science of the earth's heat; 2) a mineral or mineral assemblage whose characteristics are fixed within known thermal limits thus allowing conclusions about temperatures during process of formation; e.g., sodium, potassium and calcium concentrations in natural waters may be used to predict the last temperature of water-rock equilibration.

graben: A crustal block that is bounded by faults on its long sides, the block being downdropped in relation to the surrounding land.

groundwater: Subsurface water, especially that contained in a saturated zone, or strata, including underground streams.

horst: A crustal block that is bounded by faults on its long sides, the block being uplifted in relation to the surrounding land.

hydraulic gradient: In an aquifer, the rate of change of pressure head (height of a column of water that the pressure can support) per unit of distance of flow at a given point and in a given direction. It is usually expressed in meters per kilometer or feet per mile.

hydrologic budget (variety water budget): An accounting of the inflow to, outflow from, and storage in, a hydrologic unit, e.g., drainage basin, aquifer, or reservoir; the relationship between evaporation, precipitation, runoff, and change in water storage, is implied.

hydrology: The science that deals with all properties of water (liquid and solid) on, under and above the earth's surface.

hydrothermal: Pertaining to heated water (or aqueous solution) or products resulting from heated water, i.e., alteration of rocks or minerals by reaction of hydrothermal water.

igneous rock: A rock that solidified from molten or partly molten material, i.e., from a magma. Intrusive (plutonic) - usually having visible crystal components, and formed deep under the earth's surface, e.g., granite, diorite, gabbro, peridotite. Extrusive (volcanic) - an igneous rock that solidified on or near the surface, e.g., rhyolite, andesite, basalt; (lava flows).

inflow: The act or process of flowing in, e.g., the flow of water into a drainage basin.

inlier: An area or group of rocks surrounded by outcrops of younger rocks.

intensity (of an earthquake): A subjective measurement rating the severity of ground motion at a specific site during an earthquake. The Modified Mercalli scale uses Roman numerals from I to XII, to describe the motion that was felt and the damage to man-made structures. Intensity at a point depends not only upon the strength of an earthquake (the earthquake magnitude), but also upon the distance to the earthquake epicenter and the geologic and soil conditions at the point.

intrusion: The injection of magma into preexisting rock, resulting in plutons, batholiths and laccoliths (large scale); stocks, dikes and sills (small scale).

isotherm: A line connecting points of equal temperature.

isotope ratios: Isotope abundances given as a ratio relative to a standard rather than an absolute. Different ratios can indicate changes in environment or origin for a given chemical element. The standard is often Standard Mean Ocean Water (SMOW). Some common ratios are defined as follows:

$$\delta O^{18}(\text{in } {}^{\circ}/_{\circ\circ}) = \left[\frac{(O^{18}/O^{16})_{\text{Sample}}}{(O^{18}/O^{16})_{\text{Standard}}} - 1\right] 1000$$

Similar definitions exist for ratios of deuterium (D) to hydrogen (H) and for C^{14} to C^{12}

juvenile water: Water derived directly from a magma, reaching the earth's surface for the first time.

Langelier-Ludwig diagram: A diagram representing groupings of chemical composition of aqueous solutions.

lithic fragment: A fragment from a preexisting rock mass, usually used in describing a medium-grained sedimentary rock or certain types of volcanic deposits.

mafic: Generally igneous or volcanic rocks, containing iron, magnesium and other dark-colored minerals.

magnetic survey: Measurement of a component or element of the geomagnetic field at different locations. It is usually made to map either the broad patterns of the earth's main field or local anomalies due to variation in rock magnetization. It is often conducted as an aeromagnetic survey.

magnetotelluric survey (MT): An electromagnetic method in which natural electric and magnetic fields are measured; usually two-dimensional horizontal electric field and three-dimensional magnetic field components are recorded.

magnitude (earthquake): A measure of the strength of an earthquake or the strain energy released by it, as determined by seismologist C.F. Richter, who first applied it to southern California earthquakes. For that region he defined local magnitude as the logarithm, to the base 10, of the amplitude in microns of the largest trace deflection that would be observed on a standard torsion seismograph (static magnification = 2,800, period = 0.8 sec, damping constant = 0.8) at a distance of 100 km (62.2 mi) from the epicenter. Magnitudes determined at teleseismic distances using the logarithm of the amplitude to period ratio of body waves are called body-wave magnitudes and using the logarithm of the amplitude of 20-sec period surface waves are called surface-wave magnitudes. The local body-wave and surface-wave magnitudes of an earthquake will have somewhat different numerical values.

mélange: A mixture of rock materials derived from more than one depositional realm, usually sheared and deformed. It is a mappable body, sometimes several kilometers in length.

metamorphic rock: Rock resulting from once solid, preexisting rock subjected to extreme heat, pressure, or chemical changes. e.g., slate, schist, gneiss, quartzite, marble, serpentine.

meteoric water: Water of atmospheric origin (e.g., rain).

microearthquake: An earthquake having a magnitude of two or less on the Richter scale (cutoff may vary accoridng to user).

Mohorovicić discontinuity (Moho): A sharp seismic-velocity discontinuity that separates the earth's crust from the subjacent mantle. Its depth varies from 5-10 km (8-16 mi) beneath the ocean floor to about 35 km (25 mi) below the continents.

nanoearthquake: An earthquake having a magnitude of zero or less on the Richter scale (cut off may vary according to user.)

noncondensible gas: A gas that is not easily condensed by cooling, i.e., a substance that remains in the gas phase in geothermal processes.

outflow: The act or process of flowing out, e.g., groundwater seepage and stream water flowing out of a drainage basin.

pediment: Gently inclined erosion surface carved in bedrock, with a thin veneer of alluvium derived from the upland masses and in transit across the surface. Pediments occur between mountain fronts and valley floors.

percent reactance: The ratio of one anion species to the total anion species, expressed in milliequivalents per liter, and similarly for cation species. For example, if a water contains 0.8 meq/l calcium and the sum of all the cation species is 13.7 meq/l then the percent reactance calcium would be 0.8/13.7 or 6%. This expression provides a method of "normalizing" chemical analyses for data having a wide range of concentrations.

perched water table: Unconfined groundwater separated from an underlying main body of groundwater by an aquiclude and an unsaturated zone.

permeability: Ability of a rock, sediment or soil to transmit a fluid without impairment of the structure of the medium. A measure of the relative ease of fluid flow under unequal pressure. The customary unit of measurement is the darcy. It is equivalent to the passage of one cubic centimeter of fluid of one centipore viscosity flowing in one second under a pressure differential of one atmosphere through a porous medium having a cross-sectional area of 1 sq cm and a length of 1 cm.

porosity (effective): The ratio of the continuous void space (through which water can move) to total volume, measured at a point in a flow system.

radiometric age-dating: A method of absolute age determination based on nuclear decay of natural elements. Calculating an age, in years, for geologic materials by measuring the presence of short-life radioactive elements, e.g., carbon-12/carbon-14, or by measuring the presence of a long-life radioactive element and its decay product, e.g., potassium-40/argon-40.

recharge: The processes involved in the absorption and addition of water to the zone of saturation.

reinjection well: A well in which fluid is introduced; often used to dispose of waste liquid or possibly to replace groundwater removed from strata which might subside if the water were permanently removed.

rift zone: A system of crustal fractures, usually producing a valley or graben-like depression.

sag pond: A small body of water in a depression formed because active or recent fault movement has impounded drainage.

salinity: Total quantity of dissolved salts in water, measured by weight in parts per thousands or parts per million (ppm) with the following qualifications: all carbonate has been converted to oxide, bromide and iodide to chloride, and all organic matter completely oxidized.

sedimentary rock: A rock resulting from the consolidation of loose organic or inorganic fragmental material that has accumulated in layers, i.e. 1) clastic sediments, e.g. shale, sandstone, conglomerate; 2) chemical sediments precipitated from solution, e.g. gypsum, salt, carbonate; or 3) organic sediments consolidated from the remains or secretions of plants or animals, e.g. some limestones.

seismic survey: A geophysical prospecting technique that utilizes a seismic source such as a thumper or dynamite, and sensitive detection instruments to record travel times. Interpretation of this data allows the location of geologic structures such as faults and thickness of lithologic units.

sparker survey: A seismic survey in which an electrical discharge in water is the energy source (also called exploding wire).

solfataric activity: A late or decadent type of volcanic activity characterized by the emission of sulfurous gases from the vent.

specific yield: The ratio of the volume of water a given mass of saturated rock or soil will yield by gravity to the volume of that mass.

Stiff diagram: A closed polygon representing the chemical characteristics of a substance. Distinctions between substances can be easily observed by comparison of the different polygonal shapes for each substance.

subduction zone: A region where one crustal block descends beneath another by folding or faulting or both.

temperature gradient: See geothermal gradient.

transmissivity: In an aquifer, the rate at which water of the prevailing viscosity is transmitted through a unit width under a unit hydraulic gradient.

trilateration: A method of surveying where the lengths of the three sides of a series of touching or overlapping triangles are measured (usually by electronic methods) and the angles are computed from the measured lengths.

underflow: The flow of water through the soil or a subsurface stratum, or under a structure.

volcanic rock (extrusive): A rock formed from a magma at or near the earth's surface. Usually fine-grained, sometimes solidifying as ejected from a volcano (see extrusive igneous rock).

water budget: See hydrologic budget.